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Cari Elizabeth Sadler

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Airborne lidar-aided comparative facies architecture of Yates Formation (Permian) middle to outer shelf depositional systems, McKittrick Canyon, Guadalupe Mountains, New Mexico and west Texas

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by

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Report

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Airborne lidar-aided comparative facies architecture of Yates Formation (Permian) middle to outer shelf depositional systems, McKittrick Canyon, Guadalupe Mountains, New Mexico and west Texas

by

Cari Elizabeth Sadler, M.A.

The University of Texas at Austin, 2010

SUPERVISOR: Charles Kerans

The eastern side of the Guadalupe Mountains, located in New Mexico and west Texas, represents an erosional profile along the Capitan reef margin. A complete shelf-to-basin exposure of the Upper Permian Capitan shelf margin is found on the north wall of North McKittrick Canyon, which is nearly perpendicular to the Capitan reef margin. An excellent 2-D sequence stratigraphic framework for upper Permian backreef facies has been developed by previous workers for North McKittrick Canyon (Tinker, 1998) and Slaughter Canyon (Osleger, 1998), forming the basis for observations in this study.

The goal of this study is to describe the sequence stratigraphic architecture of the Yates Formation, focusing on the Y4-Y6 high-frequency sequences (HFSs) found in the middle to outer shelf depositional systems, and to illustrate the use of airborne lidar data to quantitatively map at the cycle-scale. Seven measured sections were taken in North McKittrick Canyon. From airborne lidar, 3-D geometries of key sedimentary and

structural features were mapped in Polyworks, in addition to the sequence boundaries delineating the Yates 4-6 HFSs.

In general, major cycles exhibit asymmetry and shoal upward. Cycle boundaries are sometimes hard to delineate due to amalgamation, particularly in the shelf crest. High-frequency sequences are commonly asymmetric; they deepen and thicken upward toward the maximum flooding surface, and the boundaries between HFSs are usually marked by thick siltstones. Major HFS boundaries can be mapped across the entire dataset, and some component cycles can be observed for minimum distances of one kilometer in an updip-downdip direction. Also, some facies tract dimensions can be estimated directly from the lidar data. Measured sections indicate that the shelf crest facies tract shifts seaward with each successive HFS, while the outer shelf facies tract steps landward.

Future work that could be done with the Y4-Y6 HFSs includes 8-10 more measured sections, collection of samples for thin sections, and tracing out of contacts between facies tracts. Extensive lidar data interpretation needs to be done so that digital outcrop models demonstrating facies distributions can be produced. This would enable the development of an outcrop analog model to mixed carbonate-siliciclastic reservoirs, which would be unprecedented in this area.

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Chapter 1: Introduction

1.1 Report Objective

The main objective of this report is to describe the sequence stratigraphic architecture of the Yates Formation, focusing on the Y4-Y6 high-frequency sequences found in the middle to outer shelf depositional systems, and to illustrate the power of using airborne lidar data to quantitatively map at the cycle-scale. An excellent 2-D sequence stratigraphic framework for upper Permian backreef facies has been developed by previous workers for North McKittrick Canyon (Tinker, 1998) and Slaughter Canyon (Osleger, 1998), and forms the basis for observations in this report.

My interpretations from field work and airborne lidar data covering the Y4-Y6 HFSs of the Yates Formation will be presented as a supplement to the work of Tinker (1998). The importance of airborne lidar data lies in its unprecedented accuracy and quantification versus traditional photopan-mapping or existing 30-meter resolution digital elevation models (DEMs), with precisions of less than a meter. Digital outcrop models (DOMs) produced from lidar data are different from standard DEMs because they contain full 3-D coordinate information (X, Y, and Z values) which enables the rugosity of outcrops to be accurately represented, and also allows other attributes such as color to be added. Digital outcrop models are important because they serve as a foundation for outcrop-based geocellular models that can be used to constrain subsurface reservoir characterization models (Janson et al., 2007).

1.2 Study Area and Geologic Setting

The Guadalupe Mountains, found in New Mexico and west Texas, dip gently as a block to the northeast, [and] are bounded on the west by "basin-and-range" normal faults (King, 1948). The eastern side of the Guadalupe Mountains represents an erosional profile along the Capitan reef margin, thus it is not surprising that the Guadalupe Mountains are a premier place to observe continuous outcrop exposures from shelf to basin (Figure 1.1). A complete shelf-to-basin exposure of the Upper Permian Capitan shelf margin is found on the north wall of North McKittrick Canyon. North McKittrick Canyon trends WNW, nearly perpendicular to the Capitan reef margin, is approximately 6.5 kilometers long, and has from 350 to 550 meters of relief from the valley floor to the rim (Tinker, 1998).

The unit of interest, the Yates Formation, is Upper Guadalupian (Permian) in age and consists of interbedded marine dolomite and terrigenous siliciclastics (Figure 1.2). It was deposited on the Northwest Shelf of the Delaware Basin behind the massive Capitan reef and foreslope (Figure 1.3). The Yates Formation represents the shelfal equivalent to the massive reefal and forereef carbonates of the Capitan Formation, in addition to the basinal siliciclastics of the middle Bell Canyon Formation. The upper Yates Formation is comprised of 40-75% siliciclastic strata (Candelaria, 1982). In general, siliciclastics in the Yates Formation are laterally more extensive updip than downdip, and thicker lower in the section. The presence of siliciclastics is strongly dependent on position within the depositional profile as well as position relative to systems tract within high frequency sequences (HFSs). At outcrop, the siliciclastic sands form recessive weathering benches that diverge basinward and pinch out before reaching the shelf margin reef (Hunt et al., 2002). The sands generally have a sharp, erosive base and a gradational contact with carbonates above. Although the main focus of this study are the carbonate strata of the Yates Formation, the presence of interbedded siliclastics is important because these recessive-weathering units provide the topographic fingerprint that allows continuous mapping of both clastics and carbonates on the airborne lidar. This differential weathering and associated terraces permits careful 3-D tracing of units and comparison of strata along the canyon walls in McKittrick Canyon, providing a much higher confidence in terms of unit correlation. The combination of photo-tracing and airborne lidar mapping allows further calibration of unit dimensions, measurement of true stratigraphic thickness along otherwise inaccessible canyon walls, and the ability to remove spatial distortion associated with oblique aerial photographic images. All these characteristics feed into the ultimate goal of generating a true-scale quantitative image of Yates facies architecture.

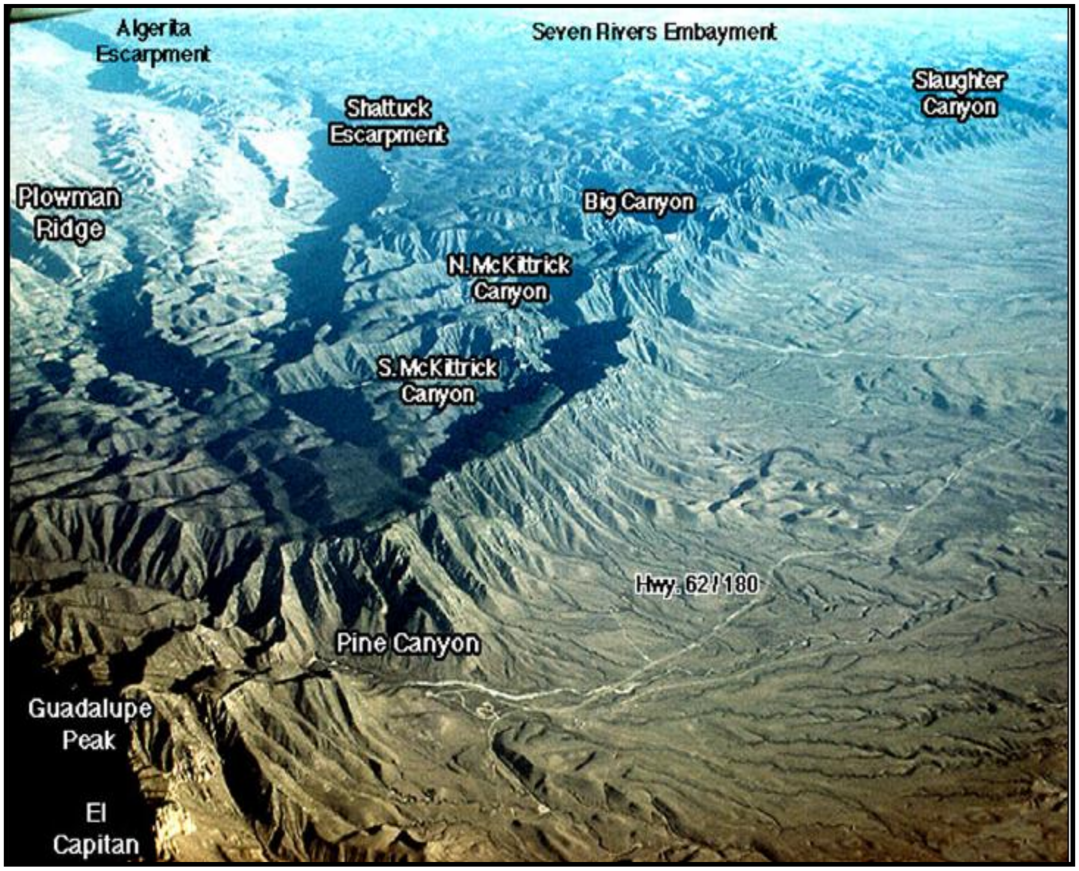


Figure 1.1 Oblique air photograph of the southernmost Guadalupe Mountains illustrating the erosional Capitan reef margin, which trends from the lower left (southwest) to the upper right (northeast). The study area, North McKittrick Canyon, is located just off center (from Kerans and Kempter, 2002).

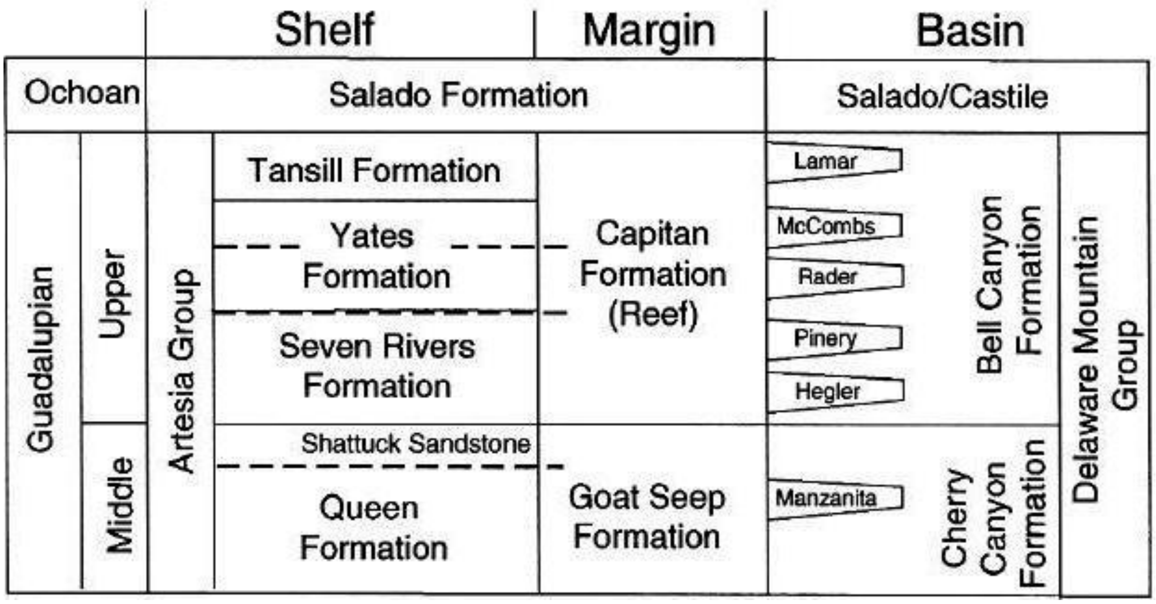


Figure 1.2 Stratigraphic chart of late Permian illustrating shelfal formations of the Capitan Reef and their margin and basin equivalents (from Rush and Kerans, 2010). The Yates Formation is time-equivalent to the Capitan Formation (margin) and the Bell Canyon Formation (basin).

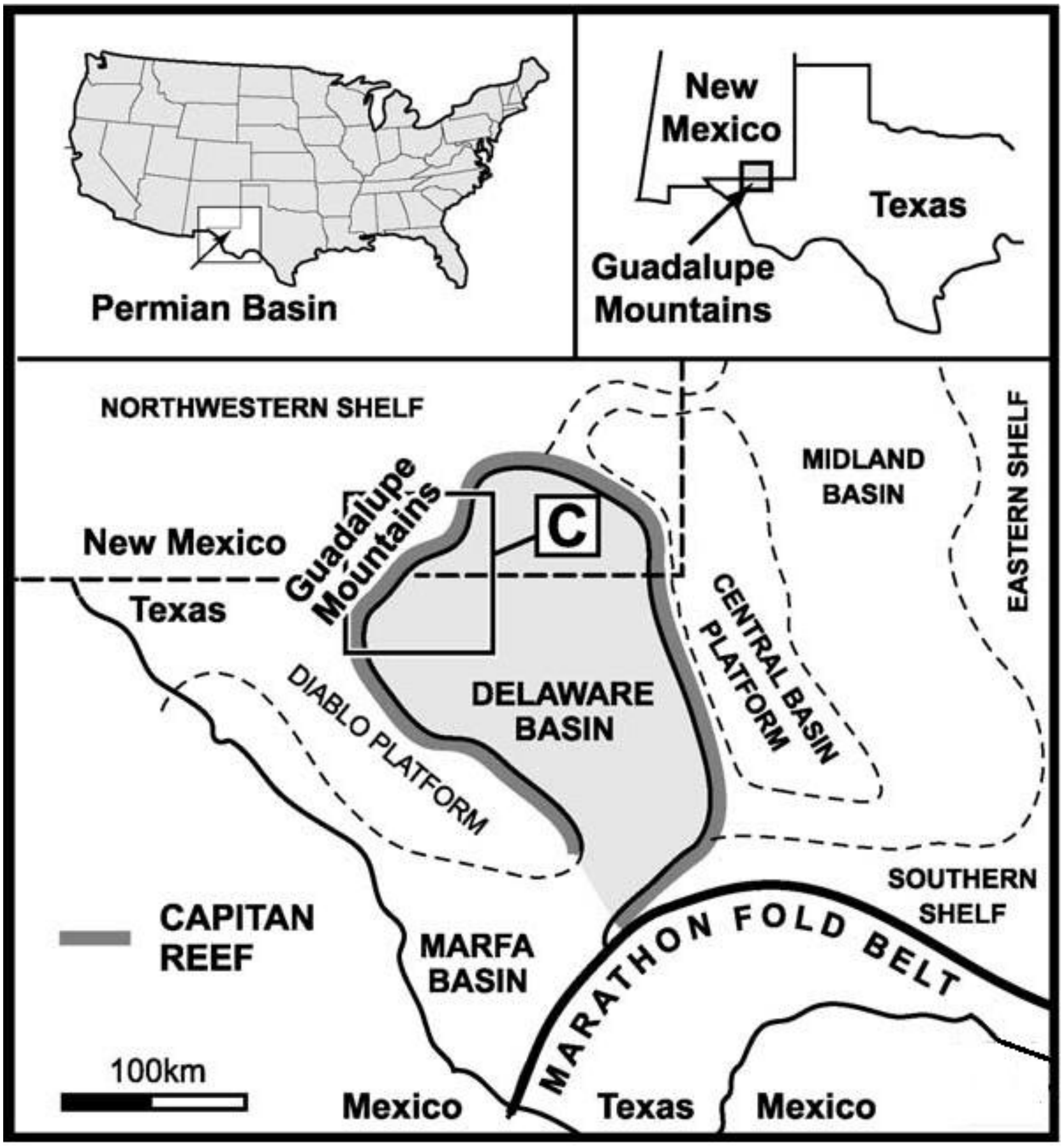


Figure 1.3 Simplified map illustrating the location of the Guadalupe Mountains on the Northwestern shelf of the Delaware basin (from Kosa and Hunt, 2005).

1.3 Terminology

At the heart of this report are the Y4-Y6 high-frequency sequences of the Yates Formation and being able to break them down to the cycle-scale. At its most basic, a high-frequency sequence (HFS) is composed of cycle sets and cycles. HFSs are bound by unconformities and their correlative conformities and are composed of lowstand (LST), transgressive (TST), and highstand systems tracts (HST), with a maximum flooding surface separating the TST from the HST. The terminology followed in this report is illustrated in figure Figure 1.4.

Facies tract terminology for McKittrick Canyon is shown in Figure 1.5. There are ten facies tracts as follows: inner shelf, middle shelf, inner and outer shelf crest, outer shelf, reef flat, reef crest, reef wall, upper slope, lower slope, toe-of-slope, and basin. The facies tracts focused on in this report are the middle shelf, inner and outer shelf crest, and outer shelf of the Y4-Y6 HFSs because this is where the best and most accessible outcrop in McKittrick Canyon is located.

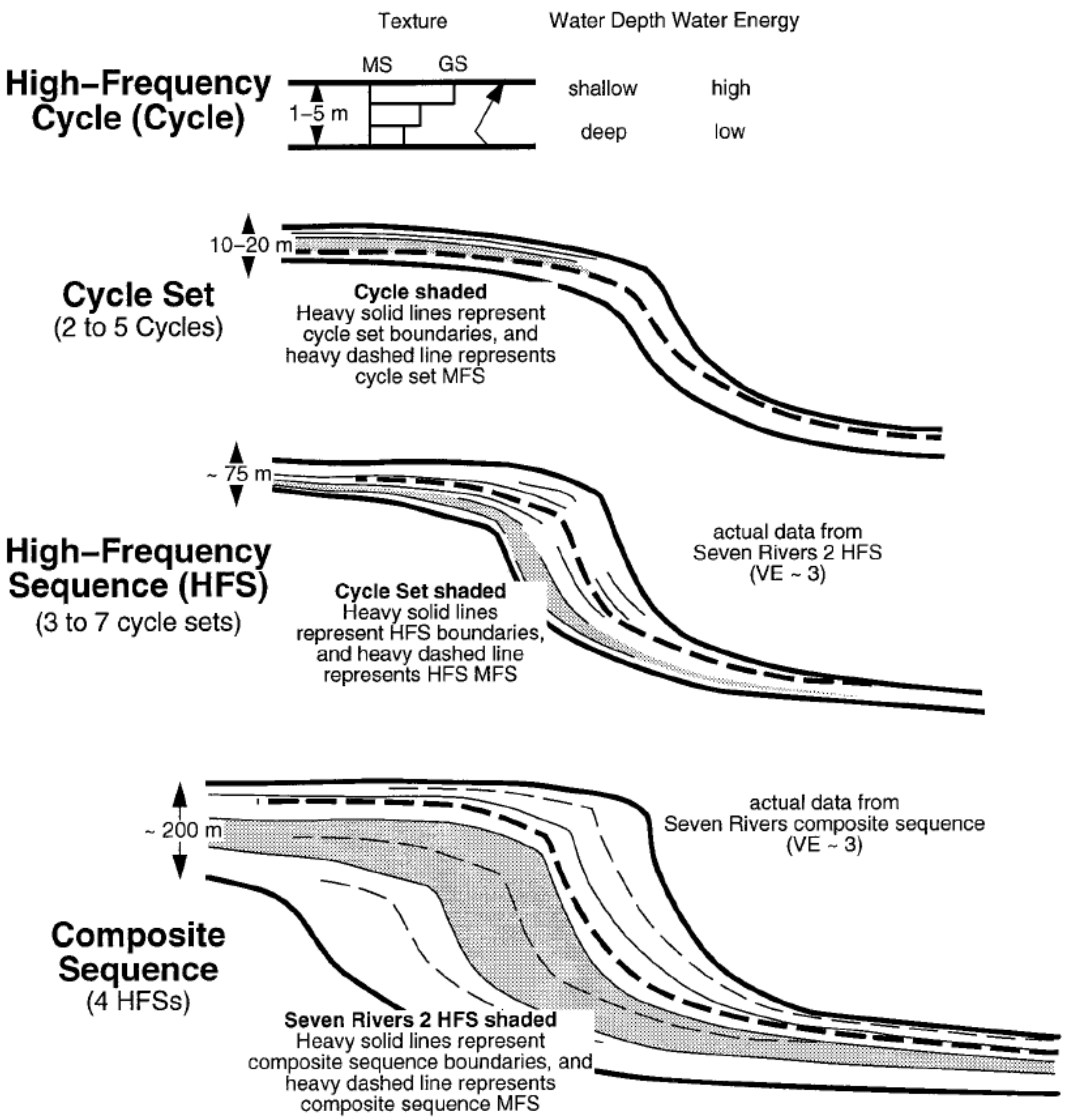


Figure 1.4 Hierarchy of cyclicity from Tinker (1998).

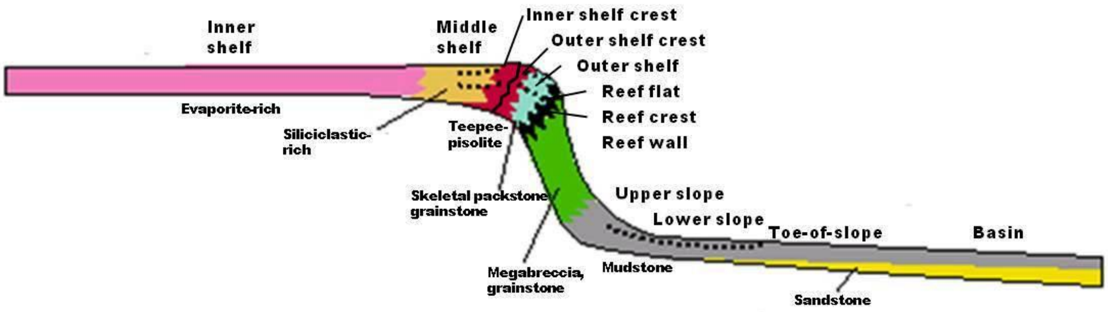


Figure 1.5 Basic depositional model for McKittrick Canyon illustrating the different facies tracts mentioned in this report. Modified from Kerans and Kempter, 2002.

Chapter 2: Outstanding Problems

2.1 Depositional Profile of the Capitan Platform and Origin of Outer Shelf Stratal Geometries in the Seven Rivers, Yates, and Tansill Formations

The controversy surrounding the depositional profile of the Capitan platform and the origin of outer shelf stratal geometries in the Seven Rivers, Yates, and Tansill Formations has been a contentious issue since early publications by King (1948) and Newell et al (1953), and continues to be discussed today. The shelf strata seaward of the teepee-pisolite complexes and landward of the reef can be observed to progressively steepen, diverge, and thicken basinward toward the Capitan reef (Hunt et al., 2002). This led Pray (1977) to refer to these beds as the "fall-in" beds. There are two very different hypotheses regarding this distinctive stratal geometry, which is distinct from modern coral-rimmed reefs with their positive shelf-edge relief.

The first hypothesis proposed to explain this profile is that the outer shelf and reef have retained the original depositional morphology of the platform (Dunham, 1972; Pray and Esteban, 1977; Yurewicz, 1977; Hurley, 1989; Kerans and Harris, 1993; Rankey and Lehrmann, 1996; Osleger, 1998; Tinker, 1998; Osleger and Tinker, 1999; Kerans and Tinker, 1999). The second hypothesis has evolved from syndepositional tilting (Smith, 1973) to tilting caused by differential compaction (Saller, 1996; Hunt and Fitchen, 1999; Longley, 1999) and finally to syndepositional down-to-the-basin tilting working alone or in addition to postdepositional tilting as the cause of the present-day strata geometries

(Hunt et al., 2002; Kosa and Hunt, 2005; Kosa and Hunt, 2006). Table 1 summarizes the different authors' views.

2.1.1 Primary Depositional Relief

Primary depositional relief, also known as the marginal mound model, is the hypothesis that carbonate grainstones flanked the seaward side of the shelf crest as foreshore and shoreface deposits, and progressively less grainy rocks were deposited in the outer shelf towards the shelf margin, as water depth and associated energy decreased (Tinker, 1996). The reef is placed in shallower water depths over time.

The main evidence for this hypothesis comes from the observation that facies along the seaward-dipping stratal surfaces demonstrate a distinct deepening trend towards the reef, matching the observed present-day profile. Quantification of the relative water-depth changes is difficult, as absolute depths from ancient facies are not directly observable. Hurley (1989), using geopetal measurements from outer shelf strata, suggested that the dips observed recorded only the regional 4-5° NE tectonic tilt plus primary depositional dip of between 4 and 15°. This conclusion has been supported by work of several recent papers (Rankey and Lehrmann, 1996; Osleger, 1998; Tinker, 1998; Osleger and Tinker, 1999). The platform profile is interpreted to represent and record the dynamic response of outer shelf paleobathymetry to relative sea-level variations. Several studies have pointed out that through facies and stratigraphic data (systematic changes in progradation and aggradation, offlap angles, shelf crest to reef distance, reef depth, and outer-shelf dip angle at both the HFS and CS scale that can be correlated around the basin) that outer shelf stratal geometries cannot be explained by differential compaction or postdepositional tilting (Figure 2.1) (Osleger, 1998; Tinker, 1998; Osleger and Tinker, 1998).

2.1.2 Differential Compaction

This hypothesis that the fall-in strata architecture of the outer shelf is of secondary (non-depositional) origin, also known as the barrier reef model, has evolved over time from differential compaction being the mechanism for basinward tilting (Smith, 1973; Saller, 1996; Hunt and Fitchen, 1999; Longley, 1999) to differential compaction coeval with growth faulting and folding being the mechanism (Hunt et al., 2002; Hunt et al., 2005; Kosa and Hunt, 2006), with faulting having a significant impact on the stratigraphic architecture and diagenesis of the platform. Recent structural and stratigraphic evidence for the differential compaction coeval with growth faulting and folding model demonstrates that back-reef strata are cut by syndepositional dip-slip faults in the outer 5-6 km of the platform and that the fault systems extend 33 km along strike parallel to the platform margin (Hunt et al., 2005). Kosa and Hunt (2006) have shown that these syndepositional faults and fracture systems are normally karst-modified and are filled with sediments, cements, and fauna of Permian age. It has been noted that faulting is most easily seen in the Y1 and Y2 HFSs, but hard to discern in the Y3 and Y4 HFSs because of the high proportion of teepee-pisolite facies.

If syndepositional down-to-the-basin tilting working alone or in addition to post-depositional tilting is the cause of present-day stratigraphic architecture (Figure 2.2), Hunt et al. (2002) raise the question of whether or not facies tracts are well-constrained since they are based on water depth. Hunt et al. (2002) believe that there is a fundamental assumption that estimates made directly from the measurement of the preserved outer shelf relief is that it has recorded primary, and hence original, depositional bathymetry of the platform. They also believe that estimates of water depth made across the reef crest derived using this method should not be used to support the interpretation that the preserved outer shelf profile represents a primary dip, or vice versa, as it relies on circular reasoning (Hunt et al. 2002). This, however, is not necessarily true because facies in the Yates composite sequence fall below fair-weather wave base (determined to be 10 meters), which establishes a baseline from which water depth can be measured. There is also an abundance of the shallow reef indicator *Mizzia* in the Yates relative to the Seven Rivers composite sequence. The barrier reef model also fails to explain the progression from high-energy, supratidal-capped cycles in the shelf crest to lower-energy, subtidal-capped, fusulinid-rich cycles in the outer shelf (Tinker, 1998).

My preliminary field mapping in McKittrick Canyon matches the hypothesis of primary depositional relief, and thus supports this hypothesis. This will be looked at in more detail in a later section of this report.

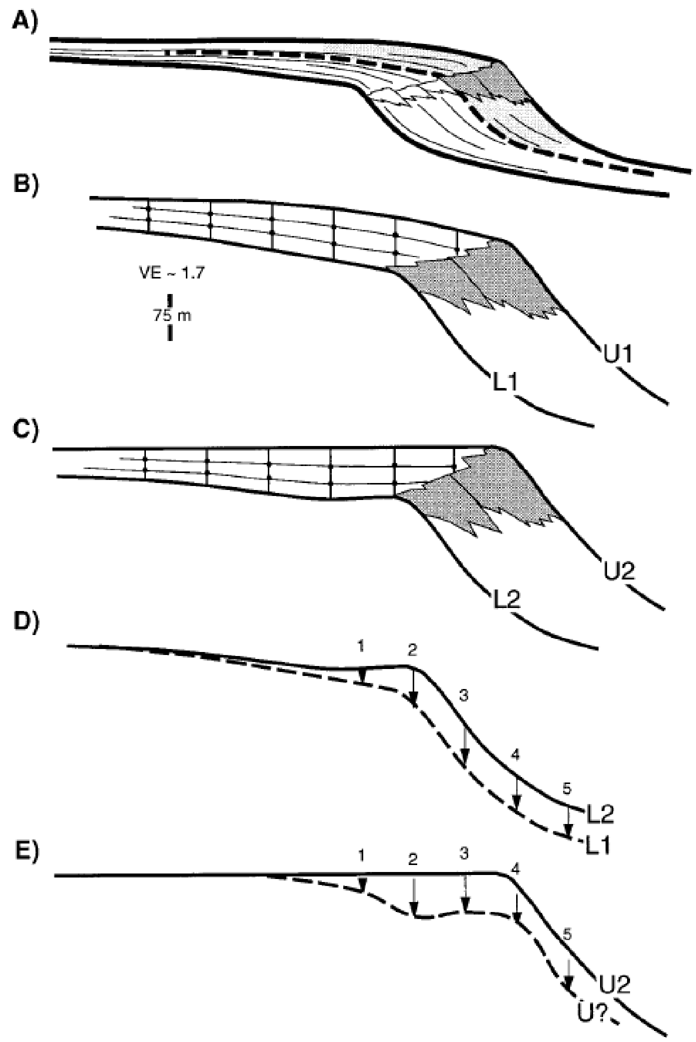


Figure 2.1 Demonstration from Tinker (1998) of how outer-shelf stratal geometries cannot be explained by differential compaction. **A)** Seven Rivers HFS showing the shaded light gray HST and shaded dark gray shelf margin observed in (B). **B)** Observed stratal geometries and bed thickness relationships seen in detail area of (A). L1: lower bounding surface, U1: upper bounding surface. **C)** (B) reinterpreted using same thickness, but with a pre-compaction barrier-reef geometry. L2: pre-compaction lower bounding surface, U2: pre-compaction upper bounding surface. **D)** Arrows represent vertical differential compaction vectors required to change L2 pre-compaction geometry to observed L1 geometry. **E)** Result of applying vertical differential compaction vectors from (D) to U2 is U?. U? does not resemble the U1 observed geometry in the least, but should if the compaction model were applicable.

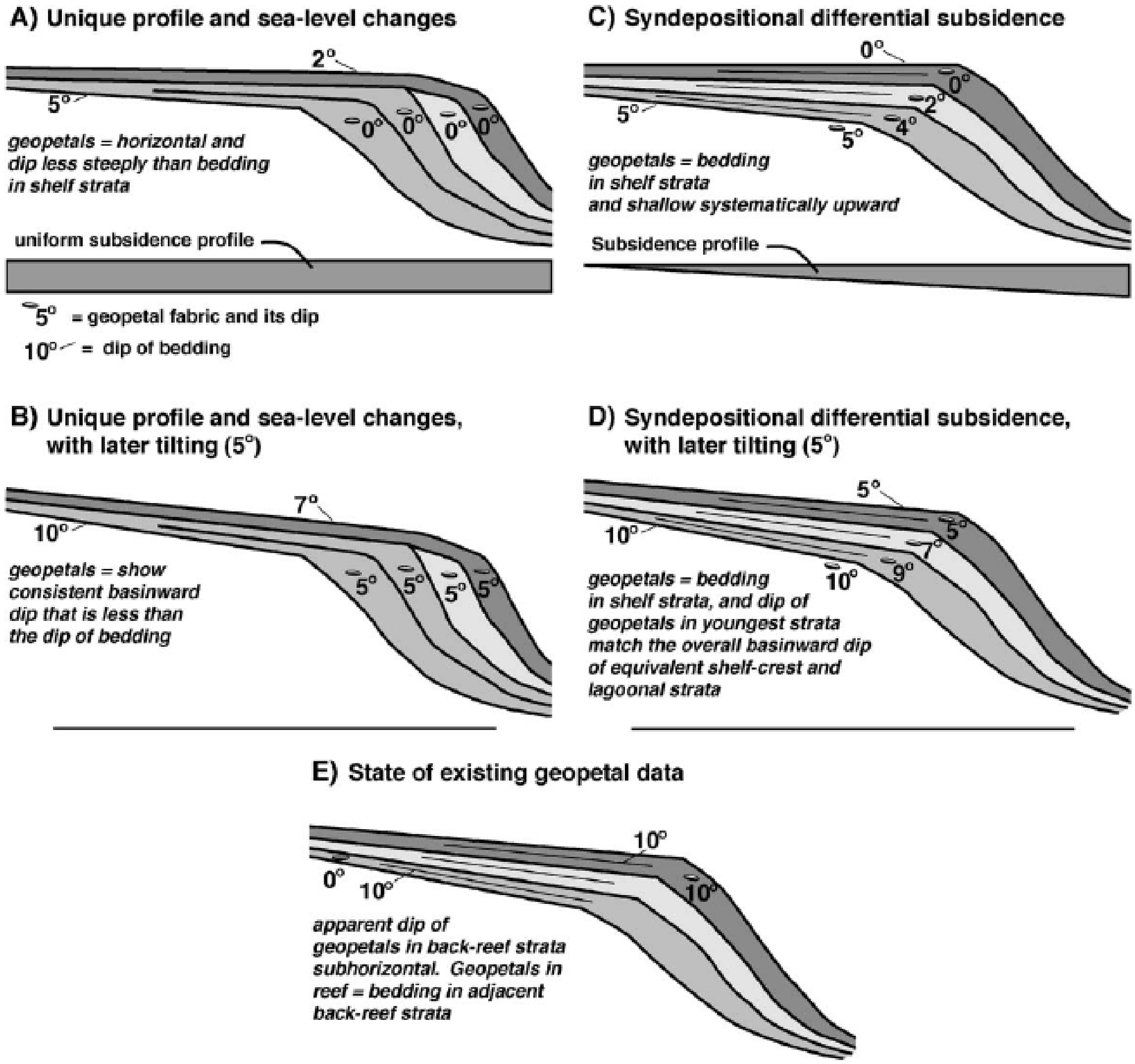


Figure 2.2 Relationships expected between geopetal fabrics and bedding from Hunt et al. (2002), with (A) and (B) representing primary depositional relief and (C) and (D) representing differential compaction. **A)** If the dip of the back-reef strata towards the Capitan reef preserves a depositional dip. **B)** Same as (A), but including the effects of 5° of post-depositional tilting. **C)** If the dips of the back-reef strata are due to synsedimentary down-to-the-basin tilting caused by differential subsidence. **D)** Same as (C), but including the effects of 5° of post-depositional tilting. **E)** Current relationship between bedding and geopetals as reported from the Capitan depositional system to date.

Author	Depositional	Compaction	Compaction + Syndepositional down-to-the-basin tilting	Data	Location
Hunt and Fitchen		**X**		Shelf architecture	Slaughter Canyon
Longley		**X**		39 field logs along the platform-to-basin profile	Upper Seven Rivers, Yates, and lower Tansill Fms., as well as their time equivalents, in Slaughter, Walnut, and Rattlesnake Canyons
Kosa and Hunt			**X**	Syndepositional folds, faults, and fractures	Walnut and Rattlesnake Canyons
Saller		**X**		20 geopetal structures	The upper middle Capitan along the Permian Reef Trail at elevations between 1920 and 2042 meters
Hurley	**X**			Geopetal structures	Fall-in beds of the Seven Rivers Fm., North McKittrick Canyon
Tinker	**X**			Facies associations, cyclicity, stratal geometry, and paleoecology	Yates and Seven River Fms., North McKittrick Canyon
Osleger	**X**			Interaction between changes in relative sea level and depositional topography, which drives seaward progradation.	Yates Formation, Slaughter Canyon

Table 1. Summary of the different hypotheses regarding the depositional profile of the Capitan platform.

2.2 Depositional Setting of Yates Fm. Silicilastics

There has been much debate surrounding the depositional setting of siliciclastics in the Yates Formation. Several models have been proposed ranging from eolian or desert fluvial transport (Fischer and Sarnthein, 1988; Mazzullo and others, 1988), offshore marine currents on a submerged shelf (Pray, 1977; Candelaria, 1982, 1989), to bypassing during sea-level lowstands and subsequent reworking and trapping of sediments during transgressions (Borer and Harris, 1991).

Mazzullo and others (1988) used Holocene mixed terrigenous sand-shallow shelf carbonate facies (i.e. Persian Gulf) as an analog and believed the deposition of sands occurred during sea-level LST when groundwater tables on the landward sabkhas were depressed. They explained that the lack of sedimentary structures resulted from dunes migrating across the outer shelf, as well as textural homogenization of remaining erg-wadi deposits by organisms and evaporative crystal growth. Blanket sands of the backreef are believed to represent eolian sheet deposits with local preserved dunes and wadi and evaporite-pan facies. Reworking by marine currents locally overprints a neritic signature on the sands, which Mazzullo and others (1988) use as evidence to support an eolian origin because eolian stratification could have easily been destroyed. Furthermore, Mazzullo and others (1988) believe the occurrence of massive, virtually textureless sheet sands in a carbonate-siliciclastic system may, in fact, be the sole remaining evidence of their eolian origin because of a lack of sedimentary structures.

Fischer and Sarnthein (1988), based on an analog with the Pleistocene eolo-marine sediments off the Saharan west coast, believed sands of the mid-Permian in the Delaware Basin were segregated into a dune phase due to trade-winds transporting detrital material from the ancestral Rockies and other uplifts, while fine sand and silt and clay were carried as dust by the wind. Fine sand and silt settled to form topography mantling, laminated siltites, while clay was carried on beyond the Delaware Basin. Dunes fed shoal-water sand wedges during times of low sea level when dunes were driven across the platform to the shelf edge, causing grain flow and turbidity currents from sand coming off the wedges to move the sand to depth and deposit it in channels carved in the basin flank. Eolian dust and sand were subsequently mixed together on the platform by flash floods prior to migration to the shelf edge.

The Borer and Harris (1991) model is the only model tied to orbitally forced, or Milankovitch, eustatic fluctuations. They described six siliciclastic facies on the Yates shelf using cores, thin sections, and wireline logs, and then assessed the cyclostratigraphy of the Yates Formation to estimate the timing of Yates deposition. The basis of this model is that siliciclastics dominated the shelf during the lowstand, asymmetric, 400 k.y. eccentricity cycles, whereas carbonates were deposited during higher stands of relative sea level (Borer and Harris, 1991). The position and character of sand depocenters on the Yates shelf during lowstands was determined by a longer period third-order sea level variation. Shorter period cycles controlled the heterogeneity within the 400-k.y. depositional sequences.

Candelaria's (1982) model is very similar to Pray's (1977) "All Wet" model where sea level is constant and shelf phenomena can be explained by gradual and/or episodic shelf subsidence based on the absence of emergence indicators of the Capitan massive and in the shallower subaqueous environment of the Seven Rivers evaporite-carbonate transition. There is also a lack of evidence of marine flooding across the shelf crest to the inner shelf, which, according to this model, makes a significant sea level rise or fall unlikely and a constant sea level more likely. Sheet sandstones are interpreted by Pray (1977) as reflecting subsidence of the shelf area of the Guadalupe Mountains such that spilling out of lagoon waters would inhibit carbonate production and the subsidence would provide access for shallow subaqueous currents to deliver sand to the marginal mound area.

Candelaria (1982) also cites episodic subsidence as the primary control on carbonate and siliciclastic sedimentation and determined that siliciclastic intervals are nonchanneled sheet sandstones that are continuous to within a few hundred meters of the reef facies where they interfinger and pinch out abruptly against grainstone. In general, there is a lack of sedimentary structures, and when present, they are small-scale. Candelaria (1988) suggests subaqueous deposition within a shelfward-diminishing hydraulic regime. Tinker (1998) used a combination of the models proposed by Mazzullo et al. (1988) and Candelaria (1982) for his interpretations such that siltstones were delivered across the shelf into the basin by eolian and shallow-water marine-coastal processes, where they were subsequently deposited by suspension in deep water.

Candelaria (1982) and Pray (1977) emphasized a sheet-like distribution of the Yates sandstones. However, there remains a possibility that broad, low-relief channel features may exist in major lowstand siliciclastic intervals, such as in the upper Yates "Triplet" member (Candelaria, 1982). Osleger (1998) documented a seaward-thinning wedge of fine sandstone that overlies the Y3 HFS boundary that when physically traced, reveals a narrow (~2 m) channel incised 1.5 m into underlying Y2 tidal-flat facies. The Triplet Unit sandstones have been identified in McKittrick Canyon by Kerans and Harris (1993) as two distinctive recessive sandstone-based skeletal-peloid dolopackstone cycles, and thus the possibility exists that similar channel features may be present in the McKittrick Canyon data examined for this study. Channels would seem likely from a theoretical viewpoint.

Chapter 3: Sequence Stratigraphic Architecture of the Yates Fm.

Much work has been done by Tinker (1996, 1998) and Osleger (1998) on constraining the sequence stratigraphy of the Upper Permian backreef facies. There are some fundamental differences in their interpretations. Osleger (1998) found that the Yates Formation consists of four complete HFSs (Y1-Y4) and the lower half of a fifth HFS (Y5) that continues into the overlying Tansill Formation. Hunt (2003) follows this terminology as well. Tinker (1998), on the other hand, identified five whole HFSs (Y1-Y5) that define the Yates Formation. The important thing to note here is that while there are different terminologies for describing the HFSs, they describe the same thing (Figure 3.1). For example, Tinker's (1998) Y5 HFS is equivalent to Osleger's (1998) Y4 HFS.

Both studies utilized facies tracts, with Tinker using the shelf-crest supratidal, outer-shelf subtidal, and shelf-margin facies tracts and Osleger using the shelf-crest and outer-shelf facies tracts.   Tinker (1998) picked sequences based on a combination of vertical variation in component cycle sets, facies, lithology, porosity, thickness, geochemical signature, and stratal geometry interpreted from the photomosaic and from lateral tracing of contacts in the field. Osleger (1998) relied heavily on the vertical and lateral stacking patterns of meter-scale cycles as well as stratal geometries to define sequences. Tinker (1998) and Osleger (1998) defined sequence boundaries as significant exposure surfaces marking relatively abrupt basinward shifts in facies in addition to large-scale changes in lateral stacking patterns. Osleger (1998) identified systems tracts within each HFS based on cycle stacking patterns (retrogradational, aggradational, progradational), while Tinker (1998) used sedimentology, stratal geometry, and vertical and lateral facies associations, with HFS Y3 serving as a model for all of the systems tracts.

An interesting difference between the two studies is that Tinker (1998) showed more TST than did Osleger (1998). Tinker found that in general, HFSs are asymmetric and deepen upward, which means that deposits are TST-dominated. He also found that the major aggradational shelf crest supratidal deposits formed in the TST of each HFS. Osleger found that the TSTs of HFSs were dominated by siliciclastics and retrograding outer-shelf carbonates, whereas the HSTs were dominated by shelf crest deposits. Both studies report low aspect ratios of shelf-crest sediment bodies, which equates to narrower and thicker deposits, but again the studies had this facies being dominant in different systems tracts. This report focuses on the Y4-Y6 HFSs located in the middle to outer shelf depositional systems.

3.1 Y4-Y6 HFS Facies Tracts

As mentioned earlier, the facies tracts contained within the Y4-Y6 HFSs in the McKittrick Canyon outcrop area are the middle shelf, shelf crest, and outer shelf.

3.1.1 Middle Shelf

In general, the low-to-moderate energy middle shelf is subtidal and contains siliciclastics with little to no outer shelf facies. The range of facies present in this facies tract includes very fine-grained sandstone, dolomitic siltstone, silty dolomite mudstone/wackestone, peloid-bioclast mudstone and wackestone, and peloid-bioclast-intraclast packstone/grain-dominated packstone (Tinker, 1996). The deepest water facies in the middle shelf is considered to be the carbonate mudstone and wackestone facies due to having the highest mud content, the presence of burrows, and lack of ooids and coated grains. Deep water here is meant in a relative term, as water depths probably never exceeded 2-3 meters. This facies is often found at the base of major cycles in the absence of siltstone. The facies in this facies tract grade downdip into the shelf crest facies tract and high-energy portion of the outer shelf facies tract.

3.1.2 Shelf Crest

The shelf crest facies tract (Figure 3.2) can be broken into two sub-tracts that relate to different depositional topography: the shelf-crest subtidal and the shelf-crest supratidal. The shelf-crest intertidal-shallow subtidal facies tract includes the facies of ooid/coated grain grain-dominated packstone/grainstone, which is interpreted as a foreshore to upper shoreface deposit. This facies occurs on the basinward side of the supratidal shelf crest and commonly has foreset bed dips of up to 4° basinward.

The shelf-crest supratidal facies tract is typified by cryptalgal laminate boundstone, composite grain rudstone, and pisoid rudstone (Figure 3.3) and is described as a complex assemblage of pisolitic composite grain dolorudstones, fenestral dolobindstones, peloid packstones/grainstones, sheet-crack fill systems, teepees, marine and vadose cements, and siltstones and fine sandstones (Tinker, 1996). Pisoid rudstones exhibit two different types of gradings, including normal and inverse. Inverse grading results from the pisoids being in a swash zone, which causes smaller pisoids to settle to the bottom and larger pisoids to settle on top, similar to what occurs when a cereal box is shaken up. This facies tract is flanked on the basinward-side by the aforementioned shelf-crest subtidal facies tract and on the landward side by the middle shelf facies tract.

The origin of pisoids in the Capitan reef has been debated. They were first interpreted as subtidal algal marine nodules, and as others questioned their algal origin (Lang, 1942; Newell et al., 1953), they were re-interpreted as vadose concretions similar to products found in some soil profiles or caliches (Dunham, 1965; Thomas, 1965, 1968) and were later termed "Permian caliche". A marginal marine, but vadose origin was suggested by Scholle and Kinsman (1974) for the pisoids after noticing that they are similar to pisoids found in the Persian Gulf. Most recently, in 1977, Esteban and Pray conducted an extensive study in the Guadalupe Mountains analyzing the pisoids there and collecting evidence to determine their origin. They ultimately concluded that the pisoids do not have a soil but marine origin, and this is currently the accepted interpretation. In thin section, pisoids from the Capitan reef display fenestral fabric, isopachous marine cement, and radiaxial cement, which are all indicative of a marine origin (Figure 3.4).

There are two distinct types of teepee complexes present in this facies tract. One type of teepee complex is found in an updip, landward position and contains carbonate cements and siltstones that fill sheet cracks. The other type of teepee complex is found in a downdip, basinward position and contains only carbonate cements. Due to these teepee assemblages, cycles can be hard to discern in this facies tract due to amalgamation, which occurs primarily in the Y5 HFS. Major cycles are easier to pick out, and are commonly indicated by a laterally-continuous truncation surface overlain by a thin carbonate mudstone to wackestone (Tinker, 1996).

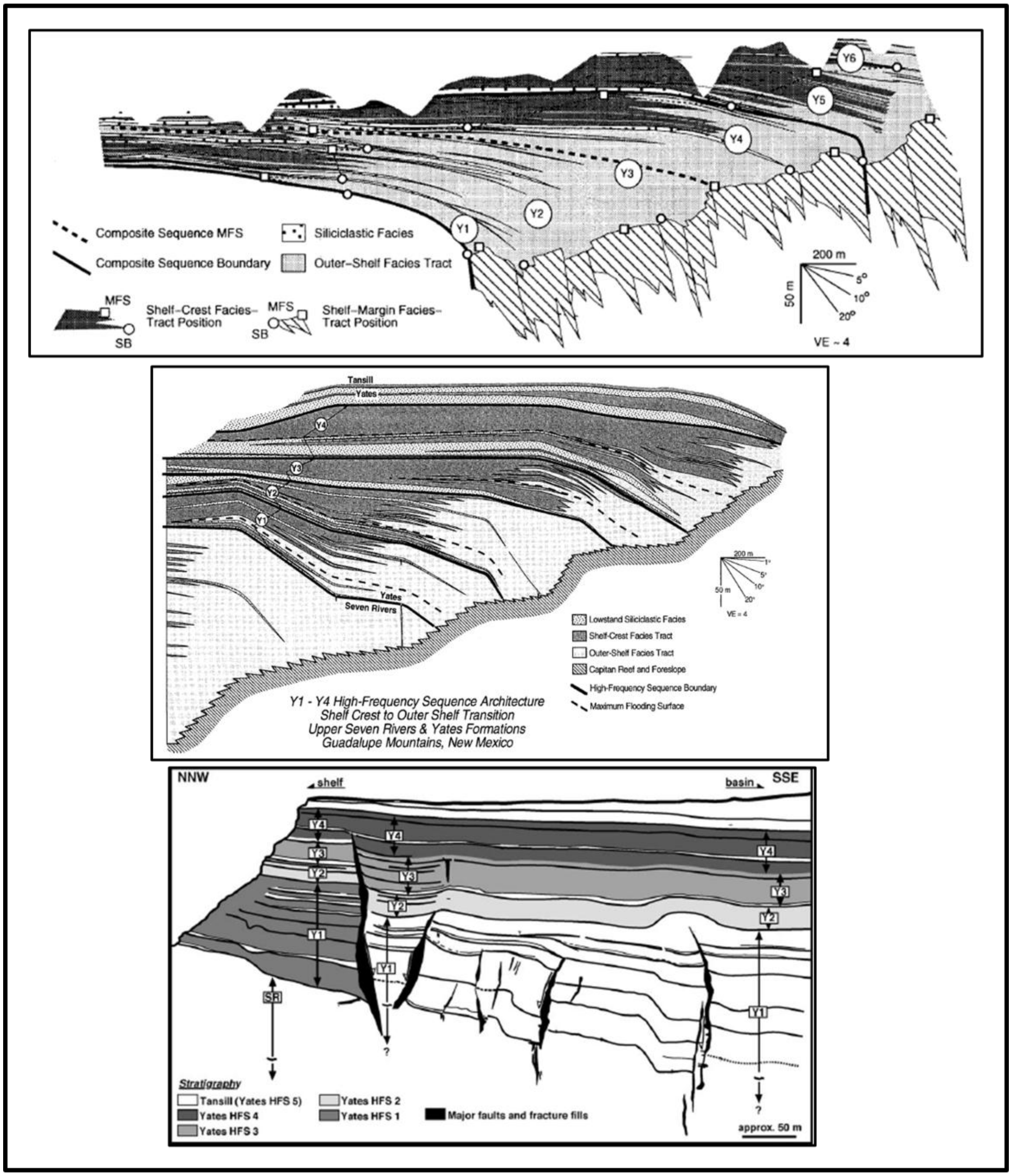


Figure 3.1 Illustration of different terminologies used to describe the Yates HFSs. A) Y1-Y6HFSs, with Y6 representing the Tansill Fm., from Tinker (1998). B) Yates sequence framework for the north wall of Slaughter Canyon at the same scale as (A). From Osleger (1998). This illustration shows Y1-Y4 HFSs with the Tansill Fm. remaining unlabeled on top. C) Hunt's (2003) version of the sequence framework of the north wall of Slaughter Canyon, showing Y1-Y4 HFSs. The Tansill Fm. is not included in this interpretation.

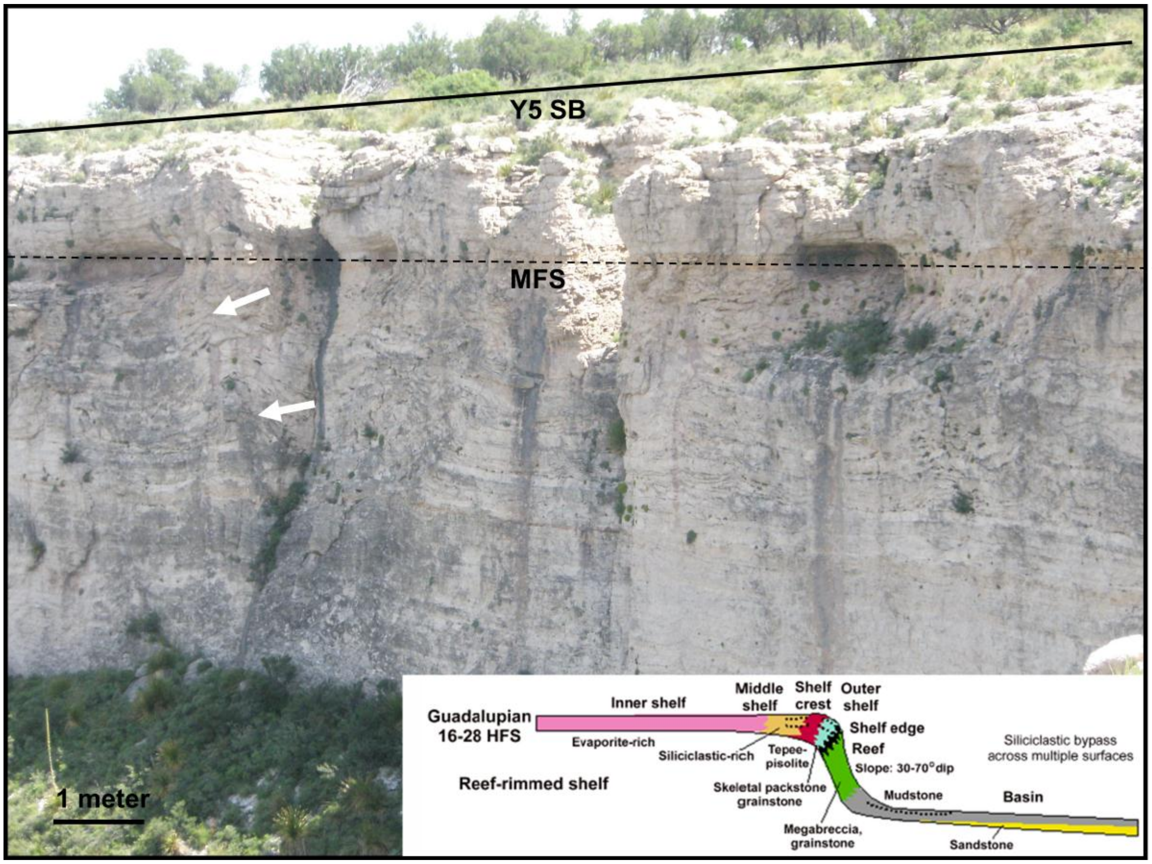


Figure 3.2 Picture taken in Y5 HFS in North McKittrick Canyon illustrating teepee complexes typical of the shelf-crest facies tract. White arrows indicate teepees. Inset diagram from Kerans and Kempter, 2002.

Figure 3.3 Picture taken from the Y5 HFS in North McKittrick Canyon illustrating a pisoid rudstone with inverse grading typical of the shelf crest facies tract.

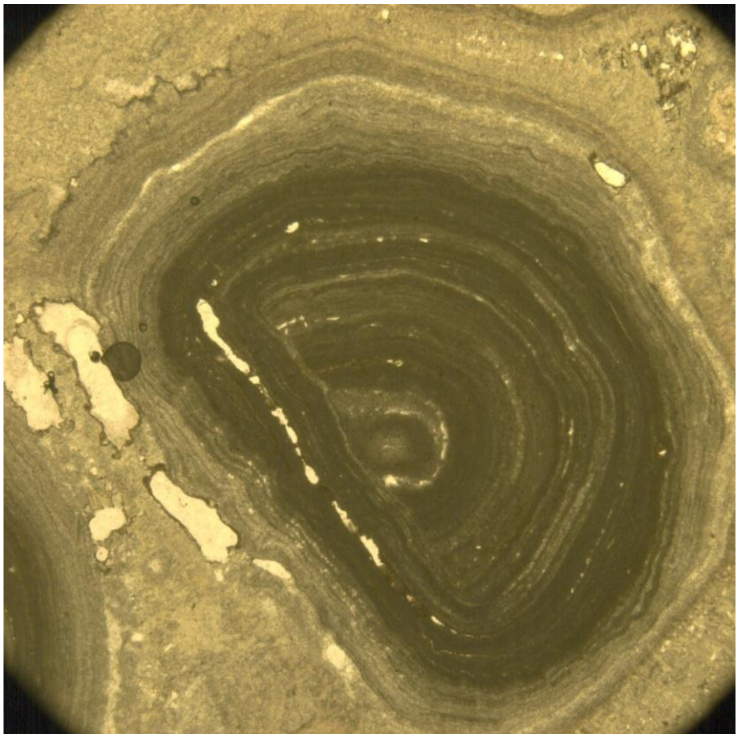


Figure 3.4 Photomicrograph of Capitan pisoid illustrating marine cement and concentric laminations. Thin section courtesy of Charles Kerans.

3.1.3 Outer Shelf

The outer shelf facies tract consists of low-energy facies and high-energy facies. The outer shelf facies tract is characterized by thinner shelf crest deposits and a shift to less massive cycles, which is indicative of a smaller amount of accommodation space in the outer shelf. Low-energy facies include dolomitic siltstone, silty dolomite mudstone/wackestone, peloid-bioclast mudstone/wackestone, crinoid-peloid-foram wackestone/packstone (Tinker, 1996). These facies are interpreted to represent the deepest water carbonate facies on the outer shelf due to having the highest proportion of mud, massive bedding, and a lack of higher energy constituents like ooids and coated grains. The importance of these deep water carbonate facies is that they are at the base of major cycles when siltstone is not present, and this lack of siltstone helps to define maximum flooding surfaces.

The high-energy facies consist of foram-*Mizzia*-bioclast packstone, peloid-bioclast-fusulinid wackestone/packstone, oncoid rudstone, and peloid-coated grain-bioclast-fusulinid grain-dominated packstone/grainstone (Tinker, 1996). In general, higher energy facies are found laterally updip from lower energy facies. The exclusion to this generalization is the fusulinid grainstone facies, which is commonly found downdip along the shelf margin due to grain mobilization or downslope transport, as indicated by grain orientation. The Guadalupian fusulinid, *Polydiexodina*, is found in the outer shelf facies tracts of the Seven Rivers and Yates Formations. *Polydiexodina* is a large (one to three centimeters in length) benthic foraminifera that is thought to have lived in water depths of 15-35 meters (Figures 3.5, 3.6).

Figure 3.5 *Polydiexodina* fusulinids occurring at Stop 14 of Bebout and Kerans (1993) Permian Reef Geology Trail Guide. These fusulinids originated in water-depths of between 15 and 35 m (Tinker, 1998) and then were resedimented both updip and downdip. The example here is from the upper slope in a minimum water depth of 200 m.

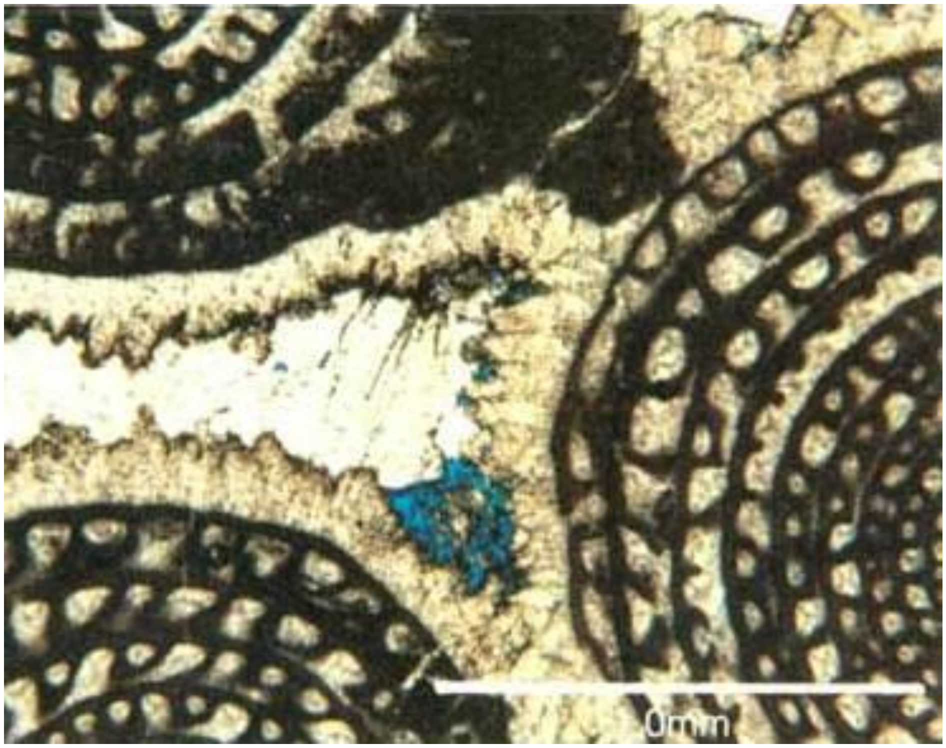


Figure 3.6 Photomicrograph of Guadalupian fusulinid illustrating internal structure (from Bebout and Kerans, 1993).

3.2 Characteristics of Y4-Y6 HFSs

The Y4-Y6 HFSs span from their zero-edge to the center of the basin and can be seen in Figure 3.7. Comparing Figures 3.7 and 3.8, it is apparent that the HFSs lose coherency moving from the west-northwest to the east-southeast toward the mouth of the canyon, and the Y4 HFS sequence boundary slopes off toward the basin. In general, major cycles exhibit asymmetry and shoal upward. High-frequency sequences are commonly asymmetric and deepen and thicken upward toward the maximum flooding surface. The boundaries between HFSs are usually marked by thick siltstones, although there is some uncertainty on where these sequence boundaries are placed within the siltstones. Borer and Harris (1991) placed sequence boundaries at the top of sands. Tinker (1996) proposed placing the sequence boundaries at the base of sands on the basis that thickest siltstones with the greatest basinward extent represent HFS boundaries and absent or thin siltstones found in a maximum landward position represent HFS maximum flooding surfaces. There is a possibility that both models could be wrong and the sequence boundaries need to be repositioned to be within the sands.

Cycle boundaries can be hard to pick out in the amalgamated shelf-crest supratidal facies tract, but are generally marked by an erosional truncation surface at the top of teepee complexes overlain by mud or siltstone. Shelf-crest deposits have a tendency to fill all available accommodation and backstep during HFS-scale transgressions and to prograde during regressions. Siliciclastics are most prevalent in Y4 and occur at the lower parts and updip positions of the HFSs. Outer shelf facies, with each successive HFS, have progressively less landward extent onto the platform top. This trend has been documented by Tinker (1998) in McKittrick Canyon as well as in Slaughter Canyon, as demonstrated in Figure 3.9 (Osleger, 1998). This is important for illustrating the along-strike continuity of facies tracts. Aspect ratios reported by Tinker (1996) for the shelf crest were low in the TST of each HFS such that deposits were narrower and thicker and higher in the HST.

The outer shelf is strongly affected by accommodation space; there is an increase in accommodation during maximum transgression that causes an upward-thickening toward the maximum flooding surface and then a subsequent upward-flattening that occurs in late HST due to a decrease in accommodation space. Generally, low-energy facies dominate the TST, while high-energy facies dominate the HST (Tinker, 1998).

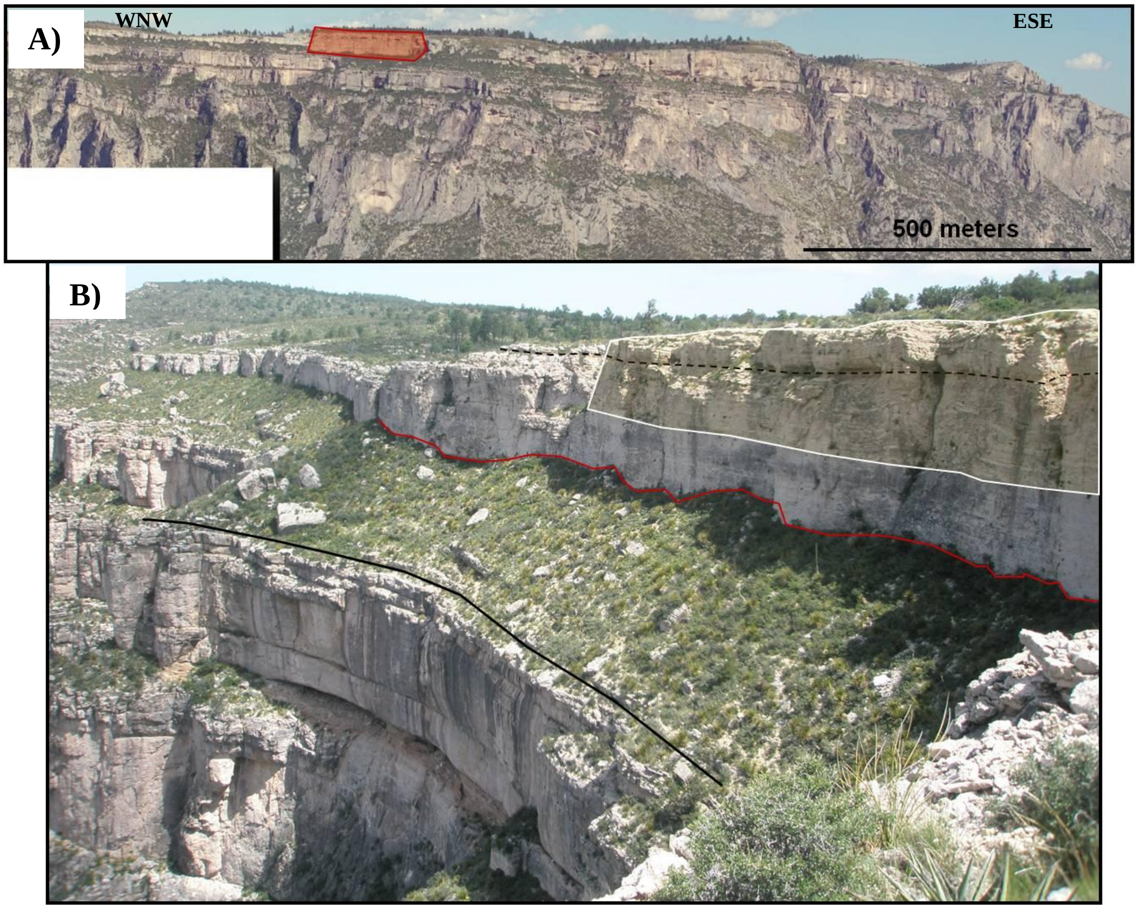


Figure 3.7 A) Location of photo taken in North McKittrick Canyon by measured section x. **B)** Y4 and Y5 HFSs. The solid black line represents the Y4 sequence boundary. The red line indicates the top of the sandstone-dominated interval. The HFSs are predominantly carbonate. The dashed line indicates a MFS, and the lightly shaded box represents the distribution of teepees.

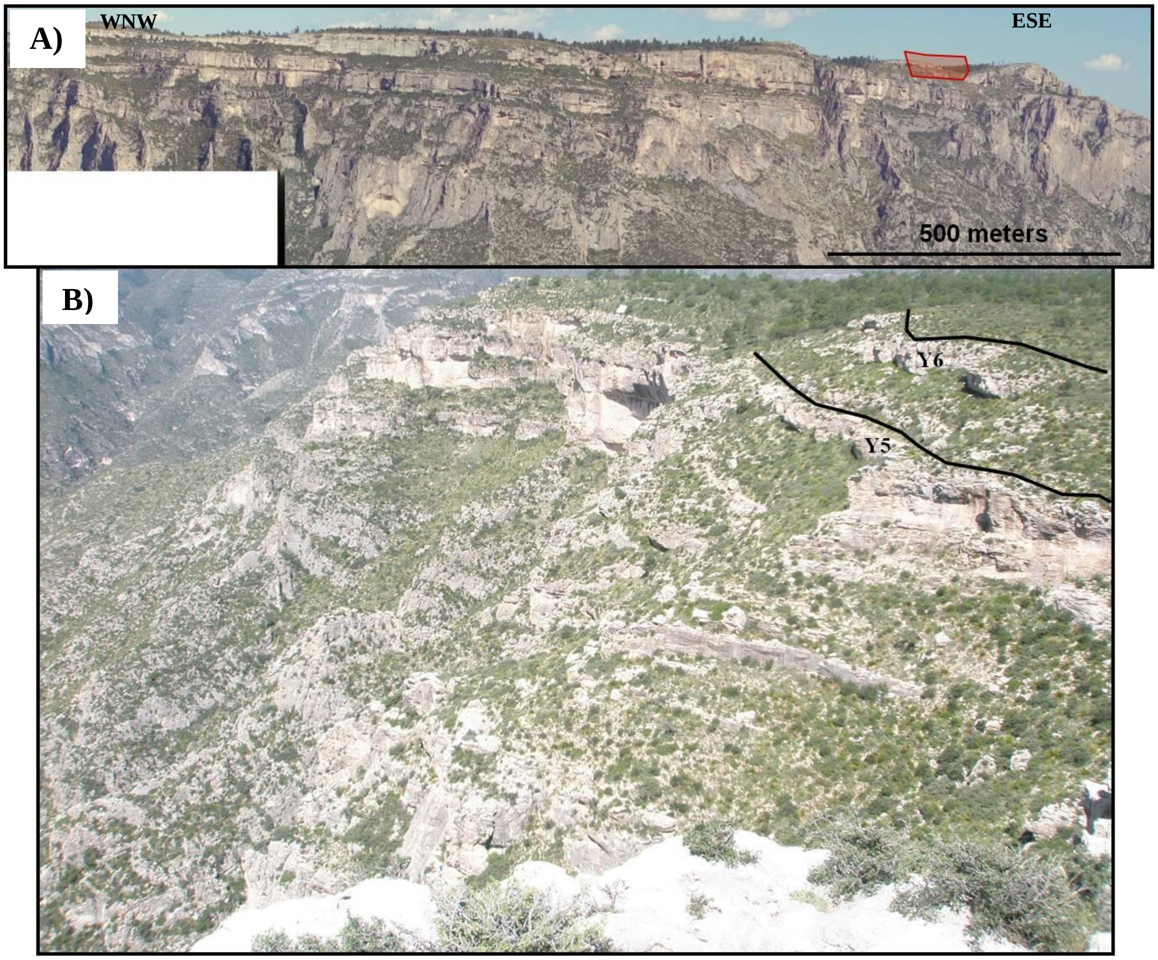
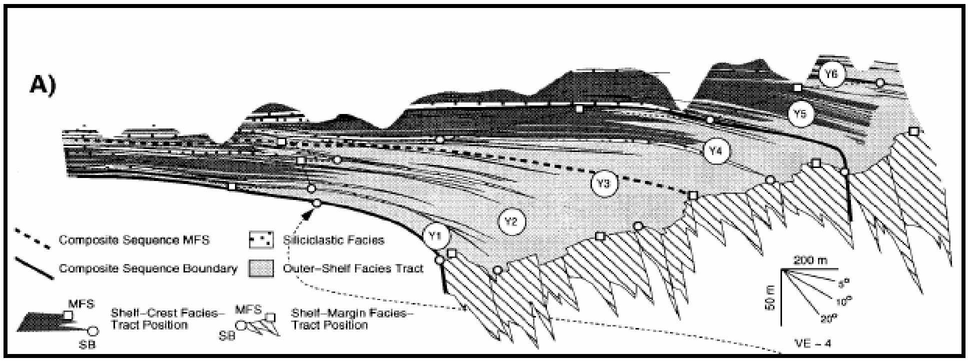
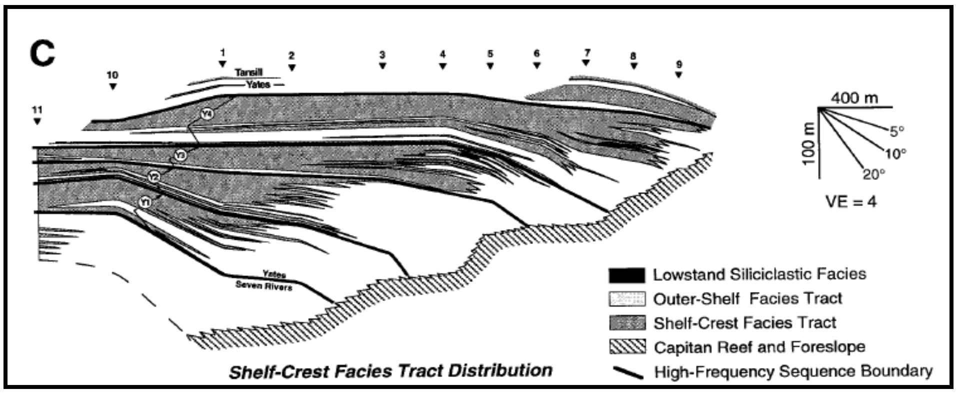


Figure 3.8 A) Location of photo taken in North McKittrick Canyon by measured section x. **B)** Y5 and Y6 HFSs. The HFSs have lost coherency moving toward the mouth of the canyon.





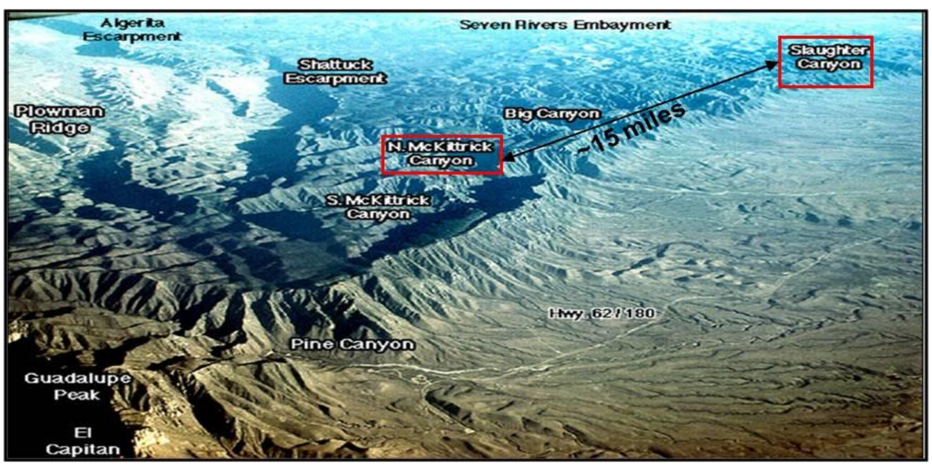


Figure 3.9 These figures are from Tinker, 1996 (top) who worked in North McKittrick Canyon and Osleger, (1998) (middle) who worked in Slaughter Canyon. Illustrated in both figures is the shelf-crest facies tract stepping basinward with each successive HFS, which supports along-strike continuity of the facies tracts spatial distributions between canyons. The bottom picture shows the distance between the two canyons, ~15 miles (modified from Kerans & Kempter, 2002).

Chapter 4: Methodology

Some fieldwork and airborne lidar interpretation has been done to meet the objectives of this report. The combination of fieldwork and lidar interpretation would enable a high resolution sequence stratigraphic characterization of the Yates Formation 4-6 high-frequency sequences to improve the current stratigraphic architecture of these sequences in McKittrick Canyon.

From airborne lidar, 3-D geometries of key sedimentary and structural features were mapped in Polyworks (a Computer-Aided Design software) in addition to the sequence boundaries delineating the Yates 4-6 HFSs. The traces of measured sections done for this report were also mapped in Polyworks.

Measured sections were measured in standard fashion with a Jacob's Staff and located in Latitude/Longitude space with a handheld GPS and georeferenced with lidar data later (the Z-value is commonly inaccurate with handhelds, but the Z-value is already recorded in the lidar data so the issue with the handheld is eliminated)(Figures 4.1, 4.2). This field data serves as calibration for interpretations being made on lidar data, as described above. Both 1-D and 2-D stratigraphic techniques can be used since McKittrick Canyon exhibits a remarkably well-organized stratigraphic hierarchy (Tinker, 1996). 1-D techniques include stacking patterns, facies proportion, and facies thickness. 2-D techniques include facies distribution, stacking patterns, aspect ratios, and progradation/aggradation ratios.

Figure 4.1 This image, taken from Google Earth, shows measured sections that have been completed for this study (white boxes).

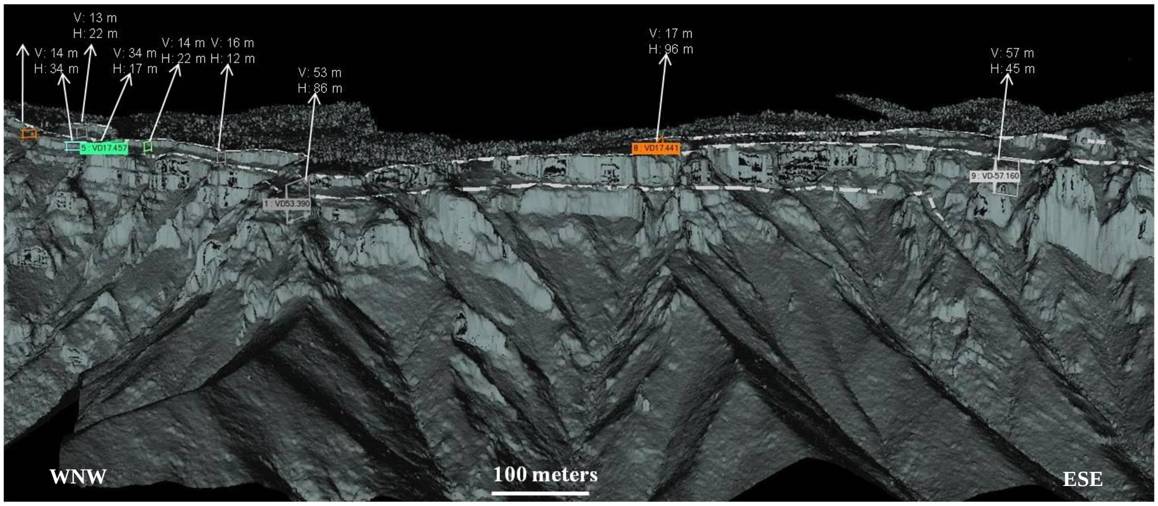


Figure 4.2 Measured section locations shown on lidar data. V=vertical height in meters, H=lateral shift in meters while measuring section.

Chapter 5: Results

Seven measured sections were taken, and nine or ten more measured sections would be needed to be able to rework the stratigraphic architecture in high-resolution at the cycle-scale. Overall, it can be seen that the shelf crest steps basinward with each successive HFS, while the outer shelf steps landward. More measured sections need to be done to determine the transition from shelf crest to outer shelf. Figures 5.1 and 5.2 demonstrate typical measured sections taken in landward positions inY4 and Y5 HFSs. Some interpretation was done on lidar, including delineating sequence boundaries for the Y4-Y6 HFSs and comparing the detail of cycles on lidar versus photopans (Figures 5.3, 5.4, 5.5, 5.6, 5.7). Preliminary results indicate that, in general, major cycles exhibit asymmetry and shoal upward. Cycle boundaries are sometimes hard to delineate due to amalgamation, particularly in the shelf crest. High-frequency sequences are commonly asymmetric and deepen and thicken upward toward the maximum flooding surface, and the boundaries between HFSs are usually marked by thick siltstones.

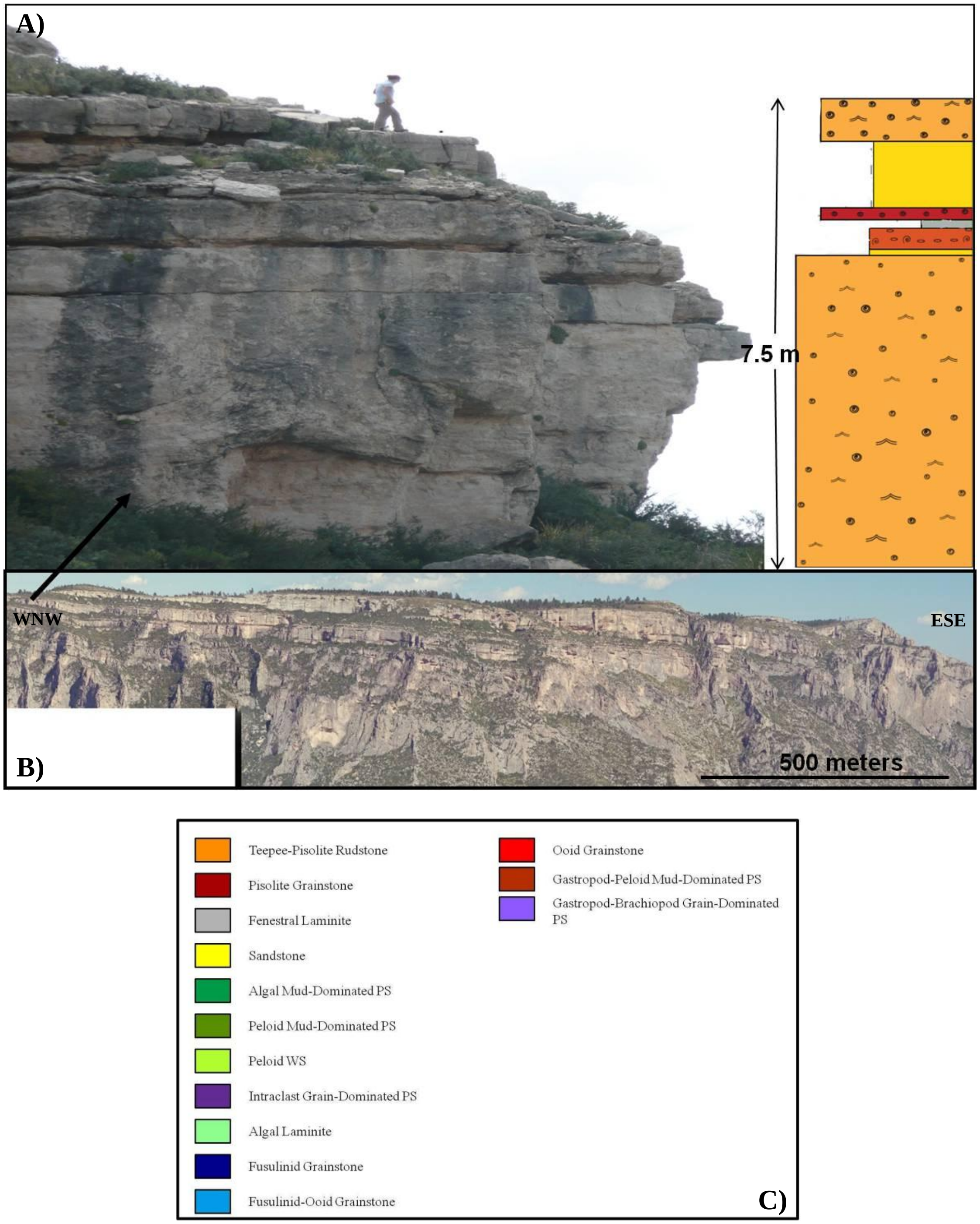


Figure 5.1 A) Measured section C-1, from the landward portion of the Y4 HFS. From bottom to top: teepee-pisolite rudstone, sandstone, peloid-gastropod packstone, fenestral laminate, pisolite grainstone, teepee-pisolite grainstone/rudstone. **B)** Location of measured section. **C)** Facies color code.

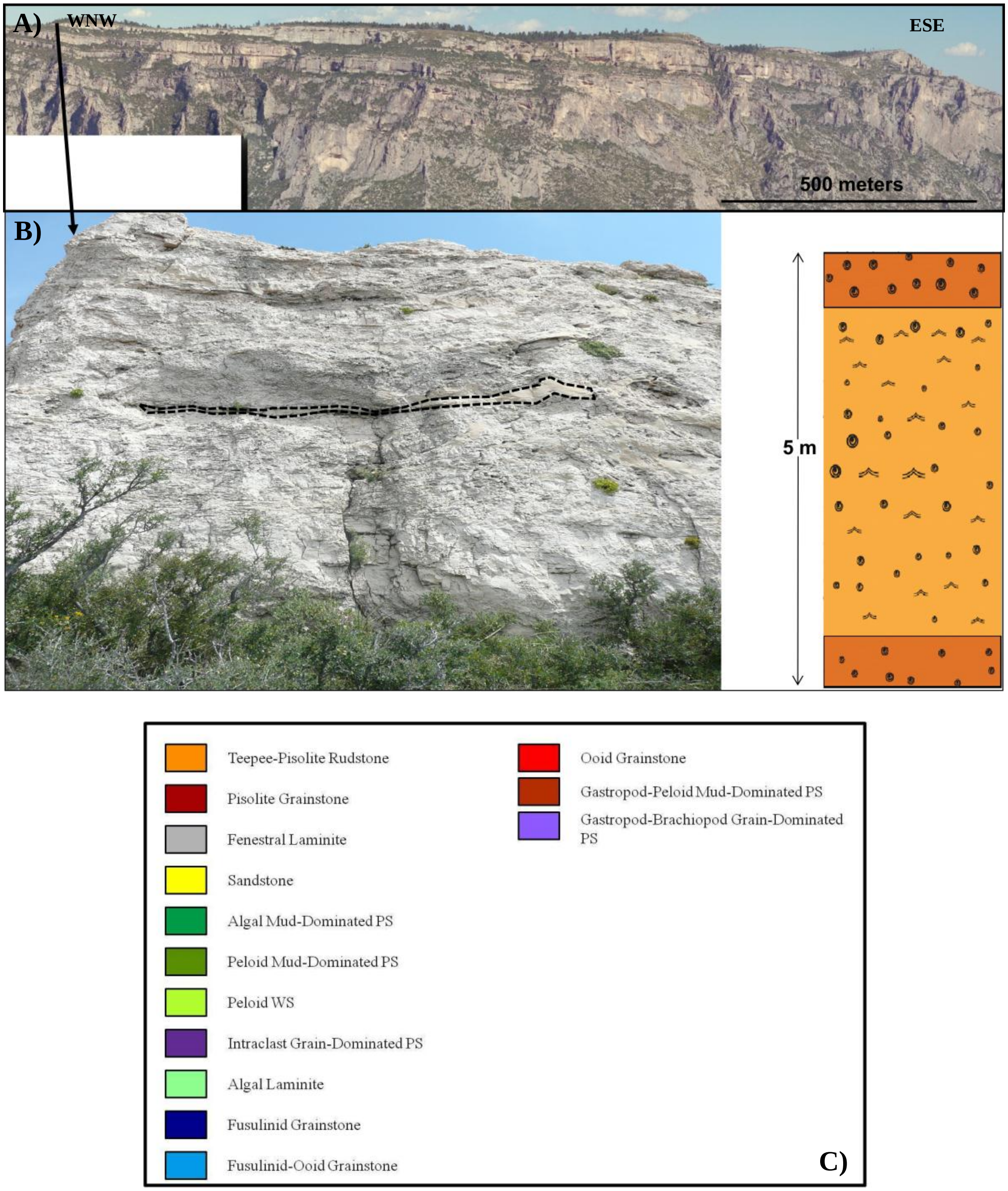


Figure 5.2 A) Location of measured section. **B)** Measured section C-2, from the landward portion of the Y5 HFS. From bottom to top: pisolite grainstone, teepee-pisolite rudstone, pisolite grainstone. Note siltstone filling sheet cracks, as indicated by dashed line. **C)** Facies color code.

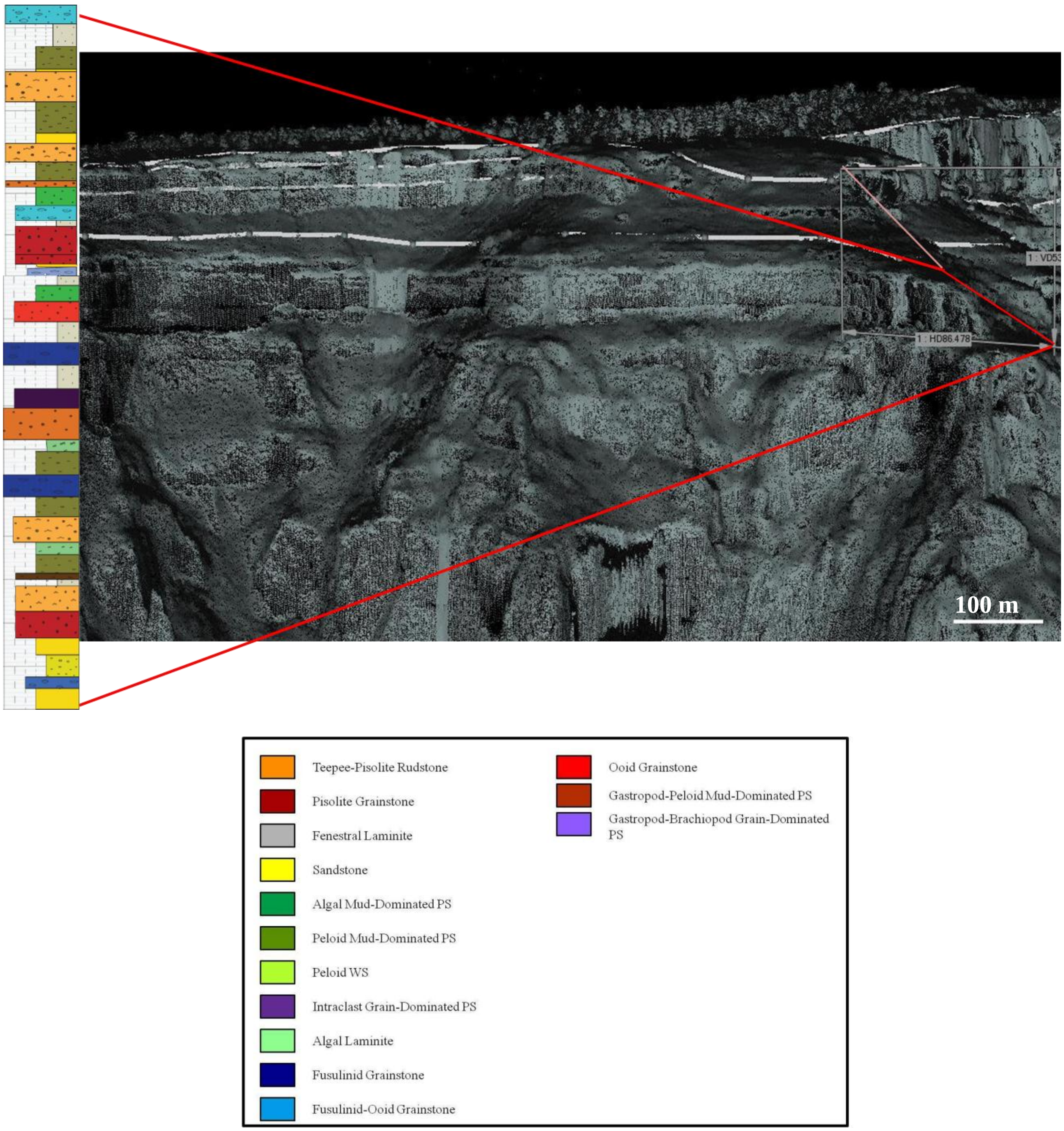


Figure 5.3 This illustration shows the cyclicity seen in the Y4 HFS, with sparse shelf crest cycles and more outer shelf cycles. Orange cycles (teepee-pisolite facies) represent shelf crest deposits, yellow cycles are sandstones, grey cycles are fenestral laminites, and every other cycle is an outer shelf deposit, ranging from fusulinid grainstones, fusulinid-ooid grainstones, algal laminites, ooid grainstones, to intraclast grain-dominated packstones.

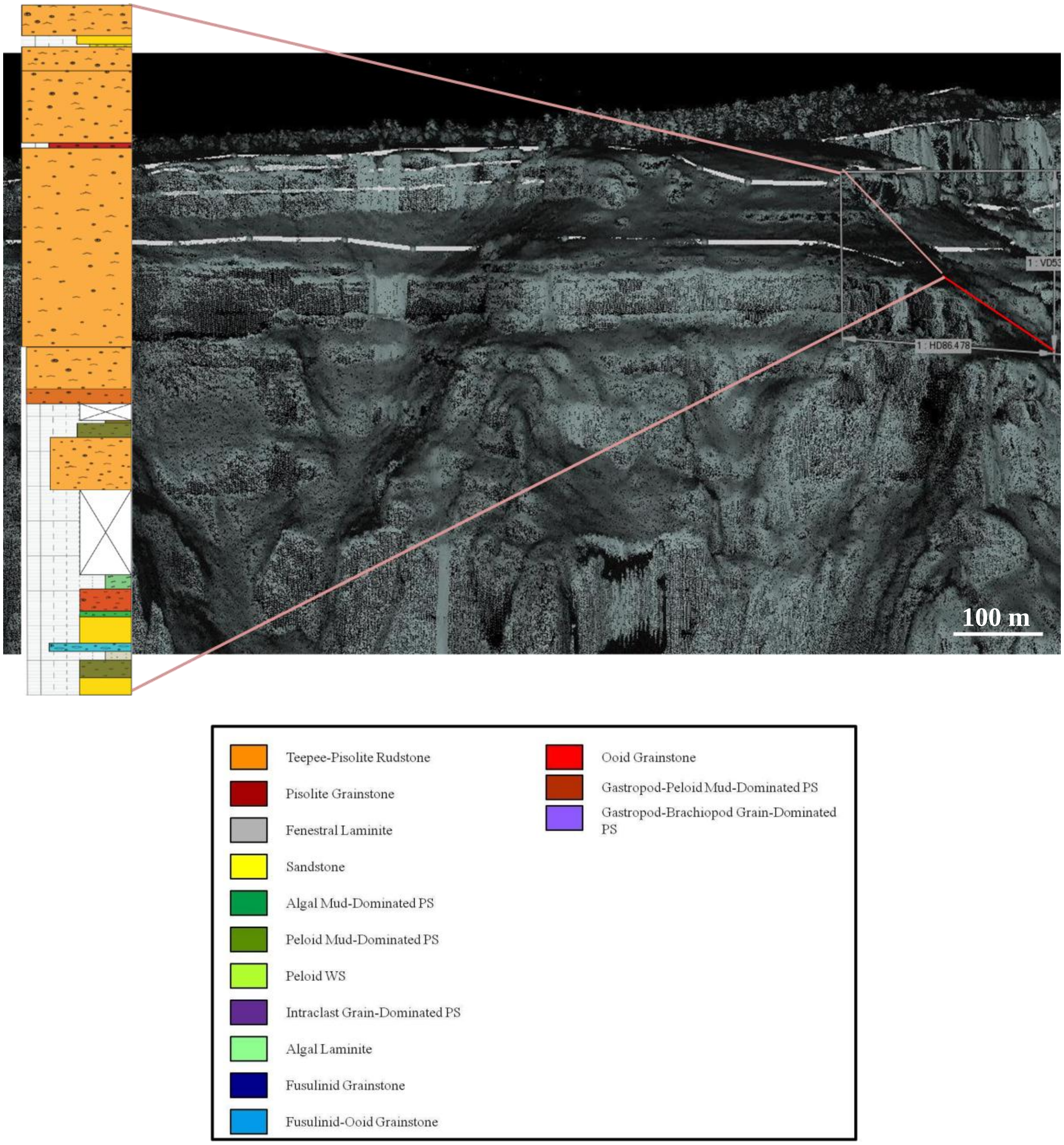


Figure 5.4 This figure illustrates cyclicity seen in the Y5 HFS, with predominantly shelf crest cycles present. All orange (teepee-pisolite facies) and orange-red cycles (pisolite grainstone/rudstone facies) are from the shelf crest. Other cycles are from the outer shelf and include algal laminites, fusulinid-ooid grainstones, and peloid mud-dominated packstone.

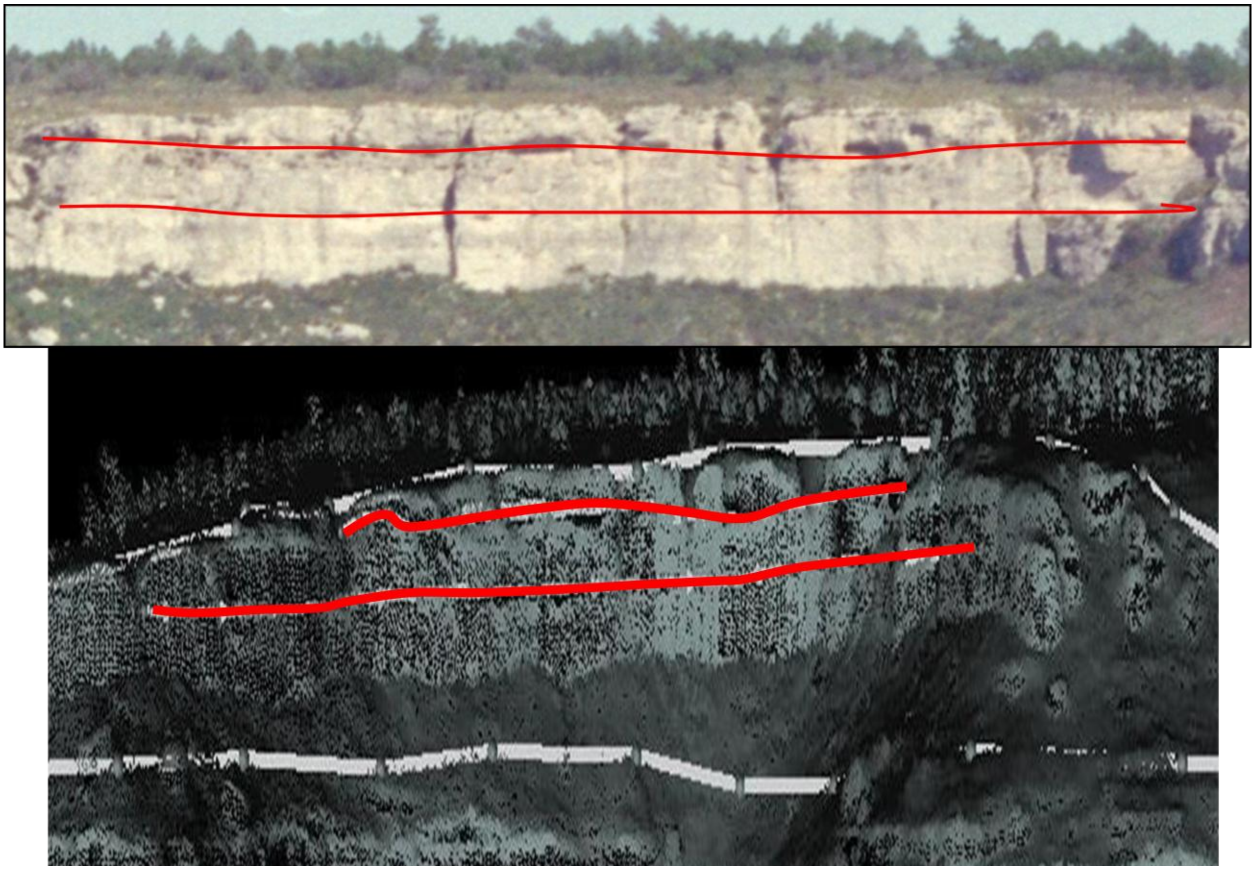


Figure 5.5 Comparison between traditional photopan (top) and airborne lidar data (bottom) of the Y5 HFS. White lines in the bottom image represent sequence boundaries. Red lines in both images represent cycle contacts. The top red line in both images is a possible maximum flooding surface.

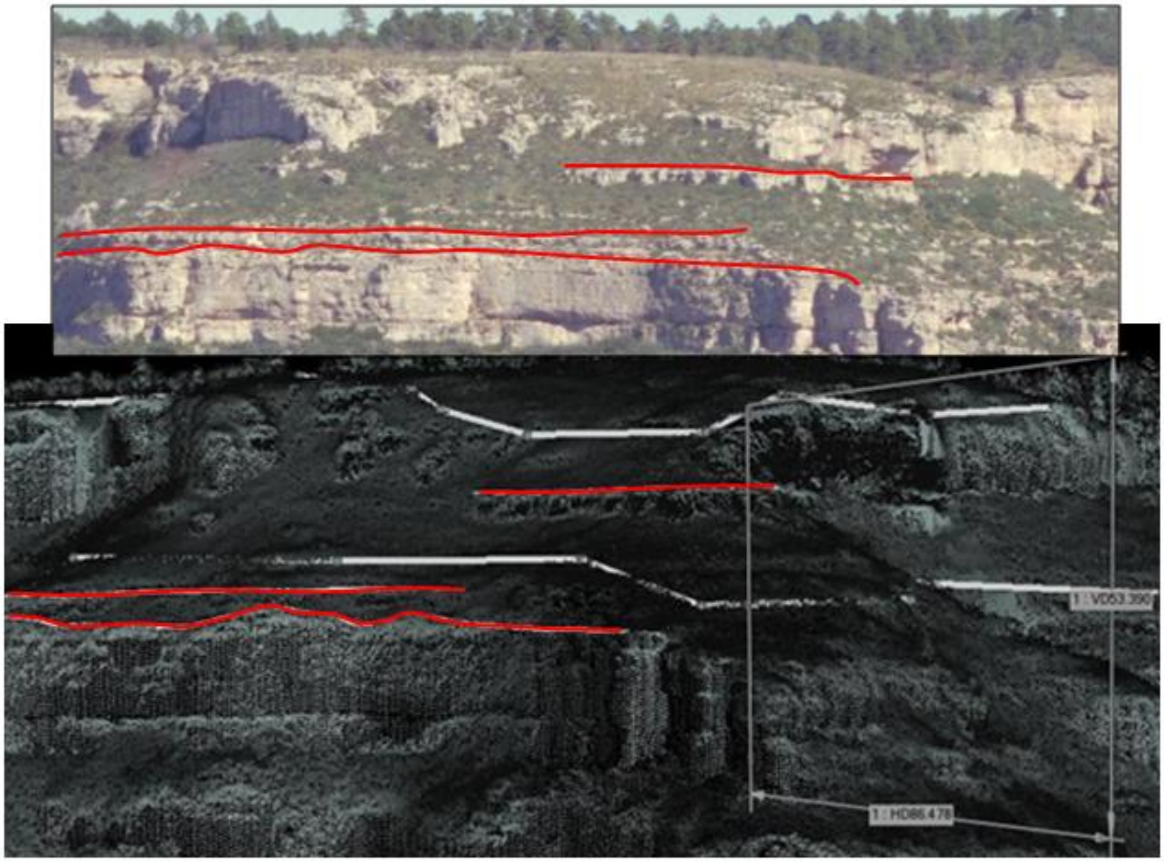


Figure 5.6 Comparison between traditional photopan (top) and airborne lidar data (bottom) of the Y4 and Y5 HFSs. White lines in the bottom image represent sequence boundaries. Red lines in both images represent cycles.

Chapter 6: Discussion and Conclusion

6.1 Discussion

Outcrop analog models are important for carbonate reservoir characterization. If future work is done, an analog for mixed carbonate-siliciclastic reservoirs can be produced based on high-resolution and quantitative sequence stratigraphic mapping of the Yates Formation 4-6 high-frequency sequences (HFSs) at the cycle-scale on lidar data. While an excellent 2-D sequence stratigraphic framework for upper Permian backreef facies has been developed by previous workers for North McKittrick Canyon and Slaughter Canyon, having 3-D models of facies and sequence architecture at the cycle-scale will be beneficial for better understanding the Y4-Y6 sequences. Previous work done by Tinker (1996, 1998) on the Y4-Y6 HFSs is foundational, but could be improved by having a better idea of how the shelf crest and outer shelf depositional environments break down at a cycle-scale instead of a major cycle-scale. The Y4-Y6 HFSs provide the best and most accessible outcrop to do so.

Results from this study indicate that constraining the stratigraphic architecture and illustrating along-strike continuity of the cyclicity of the Yates Formation through high-resolution sequence stratigraphic mapping has important implications for the application of lidar data to carbonate reservoir characterization. From this study, it was determined that major HFS boundaries, or sandstone/carbonate breaks, can be mapped across the entire dataset. Based on the figures, some component cycles can be observed for minimum distances of one kilometer in an updip-downdip direction. Also, some facies tract dimensions can be estimated directly from the lidar data due to its 3-D topography. Like Tinker (1998) and Osleger's (1998) studies, it was found from measured sections that the shelf crest steps seaward with each successive HFS, while the outer shelf steps landward. This study also supports the primary depositional relief hypothesis (also known as the marginal mound model), described earlier in this report. Through measured sections done for this study, it can be seen that carbonate grainstones flanked the seaward side of the shelf crest as foreshore and shoreface deposits, and progressively less grainy rocks were deposited in the outer shelf towards the shelf margin.

Mapping and interpreting on lidar data provides more accurate and quantitative results versus traditional photopan-mapping or existing 30-meter resolution digital elevation models (DEMs), with precisions of less than a meter. The ability to look at and interpret features that are not readily accessible (i.e. vertical walls) and an accurate representation of the outcrop are characteristics unique to lidar. Quantitative models produced from interpreted lidar data will provide an analog to mixed carbonate-siliciclastic reservoirs.

It has been demonstrated in this study that cyclicity can be seen on the lidar data just as easily as on photopans. Photopans are at a disadvantage because 3-D topography must be reduced down to a 2-D rendering, which causes distortion of vertical distance when considering the top of the canyon versus the bottom of the canyon. For example, in a photograph, 50 vertical meters at the base of the canyon wall, closer to the helicopter where pictures were taken from, appears much thicker on the photos than 50 vertical meters at the top of the canyon wall, which was further from the helicopter (Tinker, 1996). Lidar data eliminates the tedious conversion of photopan data to true vertical depth and errors that may result from doing so because there is no need to render the 3-D topography to 2-D.

6.2 Conclusion

Lidar data in concert with field work is a powerful tool with which to gain new insights into outcrops. With its 3-D capabilities and the ability to produce digital outcrop models, which are important because they serve as a foundation for reservoir characterization geocellular models and are able to model rugosity observed in outcrop, lidar data offers a versatility that can be utilized for both academic and industry purposes.

Future work that could be done with the Y4-Y6 HFSs includes finishing field work, which would entail 8-10 more measured sections, collection of samples to be used for thin sections, and tracing out of contacts between facies tracts. Extensive lidar data interpretation needs to be done to map out cycles and 3-D geometries of key structural and sedimentary features. Once geologic interpretation of the lidar data is complete, digital outcrop models that demonstrate facies distributions can be produced, enabling the development of an outcrop analog model to mixed carbonate-siliciclastic reservoirs. This would be unprecedented in this area.

Overall, there are a couple of issues that require improved understanding in this area. The problem of the depositional profile of the Capitan platform and whether it's a result of primary depositional relief or differential compaction remains unresolved due to lack of structural data, lack of independent criteria for the accurate determination of paleobathymetry of outer shelf and reef, and the interpretation of stratal geometries without supplementary data. The other problem of the depositional setting of Yates Fm. siliciclastics is difficult due primarily to a lack of identifying sedimentary and biogenic structures. There is a possibility of channelization or fluvial input, but this has not been wholly proven yet.

If future work is done, a quantitative 3-D understanding of how shoreline and shallow-shelf carbonate and siliciclastic facies respond to high-frequency eustatic shifts in a mixed-lithology setting could be produced. Questions that could be answered with such an understanding include: Do clastics bypass the shelf via channel systems or as sheets? Do shelf-crest shoal complexes record storm ridge deposition associated with base-level rise? Is the teepee-pisolite facies best developed in TST (Kerans and Tinker, 1999) or in HST as previously suggested by other workers? How do the proportions of TST and HST change in the Y4-Y6 HFSs? What are the dimensions of foreshore grainstones in each of the 3 sequences and are they changing aspect ratio as the top of the Y6 is approached? Providing answers to these questions would yield an unparalleled comprehension of the sequence stratigraphy of the Yates Formation.

References

Bebout, D.G., and Kerans, C., eds., 1993, Guide to Permian Reef Geology Trail, McKittrick Canyon, Guadalupe Mountains National Park, West Texas: Texas Bureau of Economic Geology, Guidebook 26, 48 p.

Borer, J.M., and Harris, P.M., 1989, Depositional facies and cycles in Yates Formation outcrops, Guadalupe Mountains, New Mexico, *in* Harris, P.M., and Grover, G.A., eds., Subsurface and Outcrop Examination of the Capitan Shelf Margin, Northern Delaware Basin: SEPM, Core Workshop 13, p. 305-317.

Candelaria, M.P., 1982, Sedimentology and depositional environment of Upper Yates Formation siliciclastics (Permian, Guadalupian), Guadalupe Mountains, southeast New Mexico [unpublished M.S. thesis]: University of Wisconsin, Madison, Wisconsion, 267 p.

Candelaria, M.P., 1989, Shallow marine sheet sandstones, Upper Yates Formation, Northwest Shelf, Delaware Basin, New Mexico, *in* Harris, P.M., and Grover, G.A., eds., Subsurface and Outcrop Examination of the Capitan Shelf Margin, Northern Delaware Basin: SEPM, Core Workshop 13, p. 319-324.

Dunham, R.J., 1972, Capitan Reef, New Mexico and Texas: facts and questions to aid interpretation and group discussion: Society of Economic Paleontologists and Mineralogists, Permian Basin Section, Publication 72-14, 291 p.

Esteban, M. and Pray, L.C., 1983, Pisoids and pisolite facies (Permian), Guadalupe Mountains, New Mexico and West Texas, *in* Peryt, T.M., ed., Coated Grains: New York, Springer-Verlag, p. 503-537.

Hayes, P.T., 1964, Geology of the Guadalupe Mountains, New Mexico: U.S. Geological Survey, Professional Paper 446, 69 p.

Hunt, D., Allsop, T., and Swarbrick, R., 1995, Compaction as a primary control on the architecture and development of depositional sequences: conceptual framework, applications, and implications, *in* Howell, J., and Aitken, J.F., eds., High Resolution Sequence Stratigraphy: Innovations and Applications: Geological Society of London, Special Publication 104, p. 321-345.

Hunt, D., and Fitchen, W.M., 1999, Compaction and the dynamics of carbonate platform development: Insights from the Permian Delaware and Midland basins, southeast New Mexico and west Texas, USA, *in* Harris, P.M., Saller, A.H., Simo, J.A., eds., Advances in Carbonate Sequence Stratigraphy: Application to Reservoirs, Outcrops, and Models, Society of Economic Paleontologists and Mineralogists, Special Publication, vol. 63, p. 75-106.

Hunt, D., Fitchen, W.M., and Kosa, E., 2002, Syndepositional deformation of the Permian Capitan reef carbonate platform, Guadalupe Mountains, New Mexico, USA: Sedimentary Geology, vol. 154, p. 89-126.

Hurley, N.F., 1978, Facies mosaic of the Lower Seven Rivers Formation (Permian), North McKittrick Canyon, Guadalupe Mountains, New Mexico [unpublished M.S. thesis]: University of Wisconsin, Madison, Wisconsin, 198 p.

Janson, X., Kerans, C., Bellian, J., Fitchen, W., 2007, Three-dimensional geological and synthetic seismic model of Early Permian redeposited basinal carbonate deposits, Victorio Canyon, west Texas: AAPG Bulletin, October 2007, v. 91, no. 10, p. 1405-1436.

Kerans, C., Fitchen, W.M., Gardner, M.H., Sonnenfield, M.D., Tinker, S.W., and Wardlaw, B.R., 1992, Styles of sequence development within uppermost Leonardian through Guadalupian strata of the Guadalupe Mountains, Texas and New Mexico, *in* Mruk, D.H., and Curran, B.C., eds., Permian Basin Exploration and Production Strategies: Applications of Sequence Stratigraphy and Reservoir Characterization Concepts: West Texas Geological Society, Symposium 92-91, p. 1-7.

Kerans, C. and Harris, P.M., 1993, Outer shelf and shelf crest, *in* Bebout, D.G., and Kerans, C., eds., Guide to Permian Reef Geology Trail, McKittrick Canyon, Guadalupe Mountains National Park, West Texas: Texas Bureau of Economic Geology, Guidebook 26, p. 32-42.

Kosa, E., and Hunt, D., 2005, Growth of syndepositional faults in carbonate strata: Upper Permian Capitan platform, New Mexico, USA: Journal of Structural Geology, vol. 27, issue 6, p. 1069-1094.

Kosa, E., and Hunt, D., 2006, The effect of syndepositional deformation within the Upper Permian Capitan Platform on the speleogenesis and geomorphology of the Guadalupe Mountains, New Mexico, USA: Geomorphology, vol. 78, p. 279-308.

King, P.B., 1948, Geology of the southern Guadalupe Mountains, Texas: U.S. Geological Survey, Professional Paper 215, 183 p.

Longley, A.J., 1999, Differential compaction and its effects on the outer shelf of the Permian Capitan reef complex, Guadalupe Mountains, New Mexico, *in* Saller, A.H., Harris, P.M., Kirkland, B.L., Mazzullo, S.J., eds., Geologic Framework of the Capitan reef, Society of Economic Paleontologists and Mineralogists, Special Publication, vol. 65, p. 85-106.

Mazzullo, S.J., Mazzullo, J., and Harris, P.M., 1985, Eolian origin of quartzose sheet sands in Permian shelf facies, Guadalupe Mountains (abstract), *in* Cunningham, B.K., and Hedrick, C.L., eds., Permian Carbonate/Clastic Sedimentology, Guadalupe Mountains: Analogs for Shelf and Basin Reservoirs: SEPM, Permian Basin Section, Publication 85-24, p. 71.

Mitchum, R.M., and Van Wagoner, J.C., 1991, High-frequency sequences and their stacking patterns: sequence stratigraphic evidence of high-frequency eustatic cycles, Sedimentary Geology, v. 70, p. 131-160.

Mutti, M., and Simo, J.A., 1993, Stratigraphic patterns and cycle-related diagenesis of Upper Yates Formation, Permian, Guadalupe Mountains, *in* Loucks, R.G., and Sarg, J.F., eds., Carbonate Sequence Stratigraphy: Recent Developments and Applications: AAPG, Memoir 57, p. 515-534.

Neese, D.A., and Schwartz, A.H., 1977, Facies mosaic of the upper Yates and lower Tansill formations, Walnut and Rattlesnake canyons, Guadalupe Mountains, New Mexico, *in* Hileman, M.E., and Mazzullo, S.J., eds., Upper Guadalupian Facies, Permian Reef Complex, Guadalupe Mountains, New Mexico and West Texas: SEPM, Permian Section, Publication 77-16, 1977 Field Conference Guidebook, p. 437-450.

Newell, N.D., Rigby, J.K., Fischer, A.G., Whiteman, A.J., Hickox, J.E., and Bradley, J.S., 1953, The Permian Reef Complex of the Guadalupe Mountains region, Texas and New Mexico: San Francisco, W.H. Freeman, 236 p.

Osleger, David A., 1998, Sequence architecture and sea-level dynamics of Upper Permian shelfal facies, Guadalupe Mountains, southern New Mexico: Journal of Sedimentary Research, v. 68, p. 327-346.

Osleger, David A., and Tinker, Scott, 1999, Three-dimensional architecture of upper Permian high-frequency cycles, Yates-Capitan shelf margin, Permian Basin, USA *in* Harris, P.M., Simo, T., and Handford, R., eds., Advances in Carbonate Sequence Stratigraphy—Applications to Reservoirs, Outcrops, and Models: SEPM, Special Publication

Pray, L.C., 1985, The Capitan-massive and its proximal carbonate, and minor siliciclastics of the Capitan back-reef, Walnut Canyon area, Carlsbad Caverns National Park, New Mexico, *in* Cunningham, B.K., and Hedrick, C.L., eds., Permian Carbonate/Clastic Sedimentology, Guadalupe Mountains: Analogs for Shelf and Basin Reservoirs: SEPM, Permian Basin Section, Publication 85-24, p. 25-41.

Rankey, E.C. and Lehrmann, D.J., 1996, Anatomy and origin of toplap in a mixed carbonate-clastic system, Seven Rivers Formation (Permian, Guadalupian), Guadalupe Mountains, New Mexico, USA: Sedimentology, v. 43, p. 807-826.

Rush, Jason and Kerans, Charles, 2010, Stratigraphic Response Across a Structurally Dynamic Shelf: The Latest Guadalupian Composite Sequence at Walnut Canyon, New Mexico, U.S.A: Journal of Sedimentary Research, v. 80, p. 808-828.

Saller, A.H., 1996, Differential compaction and basinward tilting of the prograding Capitan reef complex, Permian, west Texas and southeast New Mexico, USA: Sedimentary Geology, vol. 101, p. 21-30.

Smith, D.B., 1973, Geometry and correlation along Permian Capitan escarpment, New Mexico and Texas: discussion: AAPG, Bulletin, v. 57, p. 940-945.

Sonnenfield, M.D., 1991, High-frequency cyclicity within shelf-margin and slope strata of the upper San Andres sequence, Last Chance Canyon, *in* Meader-Roberts, S., Candelaria, M.P., and Moore, G.E., eds., Sequence Stratigraphy, Facies, and Reservoir Geometries of the San Andres, Grayburg, and Queen Formations, Guadalupe Mountains, New Mexico and Texas: SEPM, Permian Basin Section, Publication 91-32, p. 11-51.

Sonnenfield, M.D., and Cross, T.A., 1993, Volumetric partitioning and facies differentiation within the Permian Upper San Andres Formation of Last Chance Canyon, Guadalupe Mountains, New Mexico, *in* Loucks, R.G., and Sarg, J.F., eds., Carbonate Sequence Stratigraphy: Recent Developments and Applications: AAPG Memoir 57, p. 435-474.

Tinker, S.W., 1996, Reservoir-scale sequence stratigraphy: McKittrick Canyon and three-dimensional subsurface examples, west Texas and New Mexico [unpublished Ph.D thesis]: Boulder, Colorado, The University of Colorado, 245 p.

Tinker, S.W., 1998, Shelf-to-basin facies distributions and sequence stratigraphy of a steep-rimmed carbonate margin: Capitan depositional sysyem, McKittrick Canyon, New Mexico and Texas: Journal of Sedimentary Research, vol. 68, no. 6, p. 1146-1174.

Yurewicz, D.A., 1977, The origin of the massive facies of the Lower and Middle Capitan Limestone (Permian), Guadalupe Mountains, New Mexico and West Texas, *in* Hileman, M.E., and Mazzullo, S.J., eds., Upper Guadalupian Facies, Permian Reef Complex, Guadalupe Mountains, New Mexico and West Texas: 1977 Field Conference Guidebook, vol. 1: SEPM, Permian Basin Section, Publication 77-16, p. 45-92.